Chapter 2

Literature Review

2.1 Preamble

UPQC as a combination of series APF and shunt APF was pioneered by Fujita and Akagi in 1998 [1]. Series APF and shunt APF were connected in back to back fashion with common DC link. This topology combined the benefits of both APFs. Series APF compensates for supply voltage quality problems while shunt APF compensates for load current quality issues. Thus UPQC acts as a unified active power filter for all power quality related problems. DC link voltage regulation is included in control of of shunt APF. Effectiveness of UPQC was validated through experimental setup of 20 kVA, along-with theoretical analysis [1].

Over the years, researchers have improved upon design, topology and control of UPQC and a concise summary of developments is given section 2.2. Applications of conventional UPQC for supporting renewable DG integration are described in section 2.3. Evolution of UPQC-DG and early researches are discussed in section 2.4 and its state of art is critically reviewed in section 2.5. In the end, summary of literature survey is presented in form of research gaps.

2.2 Topologies and Control Techniques of UPQC

2.2.1 Topologies

Topologies of UPQC are many can be classified based on type of converters, type of supply system in which UPQC is place, and configuration of UPQC [2,3] (Fig. 2.1). Based converter types, three categories have been defined- Voltage Source Inverter (VSI) based topology, Current Source Inverter (CSI) based topology and Multilevel

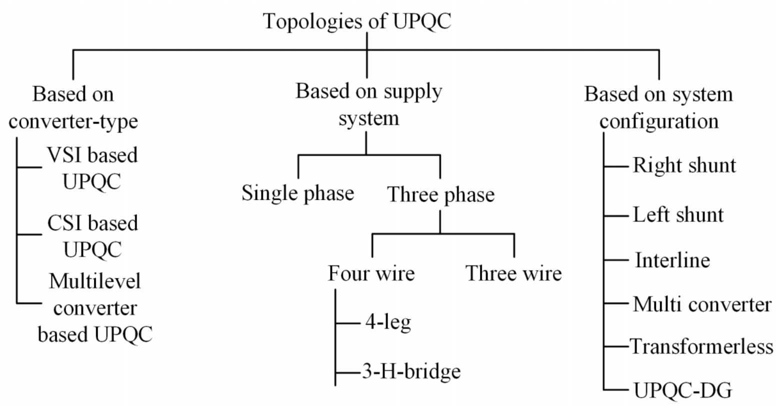

Figure 2.1: Classification of UPQC topologies

converters based topology, among which VSI based topology is most common. Multilevel converters based UPQC topologies are well suited for high power applications where device ratings put restrictions [4–6]. In [4] single phase power cell based multi-cell multilevel UPQC with discrete linear control is proposed. RTDS (Real Time Digital Simulator) based validation of 10 kV, 4 MVA Modular Multilevel Converter (MMC) based UPQC for medium voltage applications is presented in [5]. In [6] a Cascaded Asymmetric Multilevel Converter (CAMC) based five level UPQC is proposed. Hybrid modulation techniques of CAMC make implementation of UPQC control easier.

There are several single phase and three phase topologies, but three phase three wire topology is most common. Three-phase four-wire UPQC topologies are used where neutral compensation is necessary [7, 8]. Based on system configuration, various categories of UPQC topology have been defined- right shunt, left shunt, interline etc. In right shunt configuration, shunt APF is placed at right of series APF (which means shunt APF is towards load end and series APF is towards source end). In left shunt configuration, the position of series and shunt APFs are interchanged. Right shunt UPQC is much more popular than its counter part due to simplicity of control [3]. UPQC-DG is a special configuration of UPQC, which will be discussed in section-2.4.

In [9] trade off between DC link voltage requirement of series and shunt APF of UPQC is identified and a reduced DC link voltage topology was proposed for resolving this trade off without compromising the performance of UPQC. This topology results in reduced device ratings and decrement in switching losses. Simulation and experimental results validate improvements offered by this topology. Apart from this in case of DG connected at DC link, less output voltage from DG will be required, which will reduce DG converter rating.

2.2.2 Control Techniques

Control of UPQC involves measurement of load and source voltages and currents, extracting desirable (fundamental and in-phase), & undesirable components and generating reference compensating signals for series and shunt APFs of UPQC. Control algorithms for generation of reference signals are classified into two categories- time domain and frequency domain (Table. 2.1). Among time domain control algorithms most common are- Instantaneous Reactive Power Theory (IRPT) (p-q theory) [1, 10–12] and SRFT (d-q theory) [13–17] . Among frequency domain algorithms are- Wavelet transformation theory [18], and Kalman filter based control [19]. Time domain control algorithms are faster and more suited for real time control of UPQC [3]. Between time domain techniques (IRPT and SRFT), SRFT is preferred over IRPT because of its superior performance during distortion in source voltages [2].

DC link voltage of UPQC is generally regulated by shunt APF using PI controller. Apart from PI controller other techniques such as resistive optimization [20], Model Reference Adaptive System (MRAS) based PI & Adaptive Neuro Fuzzy Inference System (ANFIS) [21], Artificial Neural Network (ANN) [22], sliding mode control [23] have also been used for DC link regulation of UPQC. Reference voltage of DC link is generally held constant in conventional UPQC, but in [21], need

Table 2.1: Control algorithms of UPQC

S.N.	Time domain algorithms	Frequency domain algorithms
1.	Synchronous reference frame theory	Fourier series theory
2.	Instantaneous reactive power theory	Discrete Fourier transform theory
3.	Instantaneous symmetrical components theory	Fast Fourier transform theory
4.	Power balance theory	Kalman filter based control
5.	PI controller based algorithm	Wavelet transform theory
6.	Enhanced phase locked loop based control	S-transform theory
7.	Single phase PQ theory	
8.	Conductance based control algorithm	

of dynamically varying DC link reference voltage as per changing compensation requirements has been identified, and for this purpose, an ANFIS is applied in control of shunt APF. When magnitude of source voltage varies significantly, reference DC link voltage is changed accordingly by ANFIS. Topology used in this work is conventional UPQC which is installed in a grid connected microgrid.

Control strategies of UPQC are divided into three categories: UPQC-P, UPQC-Q, UPQC-S [3]. In UPQC-P series APF injects voltage in phase with line current. This technique requires least voltage rating of series APF and can compensate both voltage sag and well but leads to active power exchange by series APF [24]. In UPQC-Q series APF injects voltage in quadrature with line current. In this method no active power is consumed by series filter but it requires high voltage rating and voltage swell compensation is not possible with it [25].

Common disadvantage of both UPQC-P and UPQC-Q is that series APF is active only during swell or sag and remains idle in steady state, leading to its underutilization. In UPQC-S series APF injects voltage at an optimum phase angle in order to minimize kVA rating of UPQC [26]. In UPQC-S, series APF participates in reactive power compensation during steady state and reduces VA burden of shunt APF. So UPQC-S criterion is beneficial over previous two criteria but requires more design effort. Control strategy of UPQC-S is popularly known as Power Angle Control (PAC) [27–31]. Real time implementations of PAC methods are generally based on IRPT [26–28] or SRFT [30, 31].

IRPT based PAC methods are simpler than SRFT based methods but SRFT based PAC methods are more robust in grid distortions, however existing SRFT based PAC methods ([30, 31]) support only small value of power angle and thereby limit the reactive power sharing. An efficient PAC algorithm based on triangle rules for vector addition and subtractions is proposed in [29], which reduces complexity and response time of PAC method, but lacks robustness due to its being based on IRPT. PAC methods are categorized in two- fixed PAC and variable PAC [28]. In fixed PAC, power angle is only dependent on load active and reactive powers, but in variable PAC, power angle varies with on occurrence of voltage sag/swell. Sizing of converters and transformers of UPQC with PAC can be minimized with optimal power angle control, resulting in reduced overall cost than conventional UPQC [32, 33].

A dual control philosophy based UPQC, known as iUPQC, has also been proposed [34, 35], in which series APF operates in current control mode and shunt APF is operated in voltage control mode. Control methodology of iUPQC is designed to regulate grid side voltage apart from its conventional function of regulating quality of microgrid (load bus) voltage and grid current [34]. This is accomplished by providing reactive power support to grid. Thus iUPQC acts as Static synchronous Compensator (STATCOM) for grid. Experimental results show effectiveness of iUPQC in regulating grid side voltage. But it is noticed that iUPQC doesn't perform well in compensating load unbalance.

2.3 Utilization of UPQC for Supporting Renewable Integration

In various researches, UPQC has been used as an auxiliary device for supporting integration of renewable soruces such as solar PV and wind. UPQC was utilized for enhancing reactive power support and fault ride through capability of wind generator in [36]. In case of fault on grid side, voltage at PCC drops due to which wind generator has to be disconnected. But in presence of UPQC PCC voltage is maintained by series APF. Thus wind generator remains connected and supplies power to load. Besides, shunt APF provides reactive power support. Rating of UPQC was optimized by using a fixed capacitor in shunt of wind generator to share reactive power load.

In [37] a Current Source Converter (CSC) based UPQC is proposed for integration of fixed speed wind turbines. CSC has advantages of fast response to phase signal of output current, direct current control of inverters, inherent short circuit protection and long life of switches due to unidirectional nature. Due to these CSC is used in this work for additional fault ride through and reactive power support of wind based fixed speed induction generator.

Integration of renewable sources like solar PV, fuel cell through High Frequency AC (HFAC) microgrid is proposed in [38, 39]. UPQC in used in HFAC microgrid to make load currents and supply voltage sinusoidal which are not sinusoidal otherwise due to non-linearity of generators and power electronic converters. HFAC operation offers advantages of reduced size of elements like transformers, ripple filters, and reduced harmonics and ripple currents [38]. But it has its associated problems like high switching losses, electro-magnetic interference and incompatibility with existing grid infrastructure as well as consumer loads.

In [40] UPQC is used for maintaining PCC voltage of a wind farm connected to weak grid. In a wind farm connected to weak grid, PCC voltage varies due to grid disturbances as well as wind power fluctuations. Control of UPQC was based on active and reactive power sharing between series and shunt APFs via common DC link. Simulation carried out in Matlab demonstrated effectiveness of proposed method damping voltage and power oscillations of the system. UPQC with Fuzzy Logic Controller (FLC) is applied to microrgrid in [41]. Simulation was done in Matlab and results show superiority of FLC over conventional PI controller.

In [42] UPQC is utilized for fault ride-through operation of large scale PV plant connected to grid. Series part of UPQC is placed between grid and PCC, unlike in conventional UPQC where series part is placed between PCC and load. UPQC can maintain output voltage of PV plant during grid fault conditions and can absorb reactive power during grid voltage swell. Also UPQC removes grid voltage harmonics which helps in reducing response time of PLL in grid tied PV inverters. In [43] also, UPQC has been utilized for supporting frequency and voltage regulation in a weak grid with renewable sources.

2.4 Evolution of UPQC-DG

Instead of using UPQC as auxiliary device with separate grid-tie converter for supporting Renewable Energy Sources (RES) integration, directly feeding the DG power through UPQC and thus avoiding costly grid-tie converter led to conception of UPQC-DG. So, UPQC-DG offers advantage of simultaneous power quality compensation and renewable DG integration. Initial studies on integration of RES with UPQC were reported in [44–46].

In [44] solar photovoltaic (PV) was connected at the DC link of UPQC-DG. Available power from solar PV was fed to load through shunt APF. Maximum Power Point Tracking (MPPT) algorithm was also incorporated into control of shunt APF. Also control strategies for series and shunt APFs employed three PI controllers each, which would increase design and computation complexities and would slow down the performance of system. Also, PV was directly connected to DC link without a DC-DC converter or diode and the topology lacked ability to avoid reverse power-flow and safety. The proposed system was simulated in Matlab and results demonstrated compensation of voltage sag and non linear load current, however DC link voltage regulation was poor.

Integration of DG with UPQC was proposed in [45]. DG was connected to DC link through diode bridge rectifier. This topology is termed as UPQC-DG. The proposed topology of UPQC was able to compensate for grid voltage interruptions due to presence of energy source at DC bus. In case of supply interruption DG supplied power to load through shunt APF of UPQC-DG. This was additional feature of UPQC-DG besides its other power quality compensation capabilities. But DG was considered to be conventional synchronous generator, which is not environment-friendly and has high operational costs due to high fuel prices.

In [46] wind generator was connected to the DC link of UPQC-DG via AC-DC bridge power converter. This topology is similar to [45] except two differences. Firstly instead of synchronous generator, wind generation based induction generator is used. Secondly uncontrolled rectifier is replaced by controlled rectifier. In both [45, 46] authors had identified the two modes of operation for the proposed topology. First is grid-connected mode, in which UPQC-DG is connected to grid and DG is feeding power to load and remaining power (if any) is fed to grid. In this mode series APF operates in voltage control mode and shunt APF operates in current control mode. Second mode of operation is interruption mode when grid supply is unavailable and DG is feeding load through shunt APF. In this mode series APF goes out of function and shunt APF functions in voltage control mode to maintain load voltage at prescribed value. But the transitions between these modes were not analysed in these works.

Solar PV is connected to DC link of UPQC-DG through a DC-DC to converter in [47]. Control of UPQC is based on Advanced Generalised Theory of Instantaneous Power (A-GTIP). Task of regulating of DC link voltage is shared by DC-DC converter and shunt APF. When solar PV power is available, it is utilised in regulating DC link voltage and extra power is fed to load through shunt APF. Value of reference PV power fed to load is assumed to be linearly dependent on difference between actual and minimum DC link voltage. In absence of PV power, shunt APF regulates DC link voltage through a PI controller. Also in order to extract maximum power from solar PV a hybrid (offline-online) MPPT algorithm is proposed. The methodology is validated by Matlab simulation. But intermittency of solar PV power is not considered in this work, rather it is assumed to be supplying a constant power.

2.5 State of Art on UPQC-DG

In recent years, various developments have taken place in topology and control of UPQC-DG. In [48] UPQC-DG is implemented with solar PV and a single phase converter as back up source for regulating DC link voltage. In the absence of PV power this single phase converter would regulate DC link voltage instead of shunt APF which is used in previous works on UPQC-DG. The rationale behind is that if shunt APF is used for regulating DC link voltage, then it itself draws non-linear current which can not be compensated. Though use of single phase converter creates unbalance in load currents, it can be compensated by shunt APF. But using additional converter for regulating DC link voltage is costly and reduces reliability. Also, the magnitude of current required for regulating DC link voltage is only a small fraction of load current. In this work a modified MPPT method is also proposed to extract maximum power from solar PV under varying temperature and irradiation. A model reference control based UPQC-DG with sliding mode control of DC link has been developed to improve power quality compensation [49].

Design and simulation aspects of UPQC-DG are described in [50–52]. In [51], solar PV is connected at DC link with boost converter, which regulates DC link voltage and supplies PV power to shunt APF. Series APF of UPQC-DG is controlled by UVTG technique and p-q theory is used for control of shunt APF. Perturb and Observe MPPT methods is used for tracking maximum power of solar PV. MPPT algorithm generates reference DC link voltage. Difference between reference DC link voltage and actual DC link voltage decides reference PV current for feeding to load. This difference is also used for controlling duty ratio of boost converter. Simulation is carried out in MATLAB/Simulink. Results show reduction in Total Harmonic Distortions (THDs) of load voltage and supply currents from 24 % to 4%, but performance of system during absence and variation of PV power is not evaluated.

Analytical design procedures along with formulation of equations for filter parameters of UPQC-DG have been devised in [50, 52]. Design of UPQC-DG with boost converter is proposed in [50], and UPQC-DG without boost converter is designed in [52], where PV array is directly connected to DC link with a diode to avoid reverse power flow. A SRFT based control of PV fed UPQC-DG is proposed and validated for dynamic situations using Matlab simulation and hardware [50, 52].

PV based UPQC-DG controlled using dual control strategy, in which series APF operates in current control mode and shunt APF in voltage control mode, is proposed in [53]. Steady state performance of developed dual UPQC-DG and effect of steep variation in solar irradiation on its performance is studied using hardware prototype, and satisfactory results are obtained in both except peaks in DC voltage during steep changes.

Authors in [54, 55] have used UPQC-DG as central power electronic interface in a renewable microgrid. In this work islanding detection and reconnection techniques are added as secondary control to conventional UPQC-DG, which relieves individual DG converters of microgrid from burden of islanding detection and reconnection functionalities, making control of DG converters simple. Apart from this Non Detection Zone (NDZ) in islanding detection process reduces because now islanding is done centrally by UPQC-DG. Because of UPQC-DG in microgrid, individual DG converters have to supply only active power, as load reactive power requirement is met by UPQC-DG, which reduces rating and cost associated with these converters. In grid connected mode DG converters function in current control mode and secondary control of UPQC-DG monitors supply voltage and whenever this voltage violates prescribed norms, UPQC-DG issues islanding command to circuit breaker and DG converters. In islanded mode DG converters operate in voltage control mode. UPQC-DG is used as interface between AC and DC microgrids, where DC link of UPQC-DG serves as common DC bus for DC microgrid. [55].

In case of UPQC-DG, Shunt APF has to supply DG power to load along with reactive compensation, which further increases the VA rating of shunt APF of UPQC-DG in comparison to series APF. So, in case of UPQC-DG, power angle control holds more importance than conventional UPQC, and thus various PAC methods of UPQC-DG have been developed so far in recent years [56–59].

In [56] power angle control of UPQC-DG is proposed for effective capacity utilization of shunt and series APFs of UPQC. In power angle control method series APF supplies part of reactive power in an optimal way so as to reduce overall kVA burden on shunt APF. This is achieved by controlling the magnitude and phase of voltage injected by series APF. Matlab simulation carried out on UPQC-DG with solar PV connected to DC link validates effectiveness of this method in keeping kVA loading of shunt APF within limits, but this method can lead to overloading of series APF during low power factor of load, when reactive compensation requirement is high because limits on power angle are not defined. Apart from this modeling of solar PV and its intermittent nature is missing in this work.

In [57] solar PV in parallel with battery storage is connected at DC link of UPQC-DG. This topology is aimed at compensating voltage and current quality issues including supply voltage interruption during whole day operation of UPQC-DG. Solar PV is connected via High step-up DC-DC converter and battery is connected using bi-directional Buck-Boost converter. Perturb and Observe MPPT algorithm is used for extracting maximum power of solar PV. UPQC-DG is operated in PAC mode to effectively utilize series APF, but details on selection of power angle and analysis of power sharing between series and shunt APFs is missing. In control loop of shunt APF, High Selectivity Filter (HSF) is used for accurate extraction of fundamental component of currents. DC link voltage is regulated by shunt APF with help of a PI controller with squared error input to yield fast and precise regulation of DC link voltage. UVTG based Power angle control for single phase UPQC-DG with fuel cell as DG has been developed in [58]. Fuel cell can be operated as independent supply source and it can feed loads through two inverters of UPQC-DG during grid outage.

A modified IRPT (p-q theory) based PAC method of PV based UPQC-DG is proposed in [59]. The modified p-q theory is developed using Generalized cascaded delay signal cancellation, which ensures robust performance during distortion in source voltages as validated using simulation and hardware-setup results, but in optimal estimation of power angle and analysis of power sharing between converters is missing.

VA rating of UPQC-DG and its constituent converters can be optimized using PAC approach, which is not found in existing literature. Though optimum design of UPQC-DG considering its different modes of operation has bee done [60], but power angle control has not been considered in the design process.

2.6 Research Gaps

Based on exhaustive literature survey, following research gaps have been identified in control of UPQCDG. These are then taken up in this work as described in following chapters.

- Control of coventional UPQC-DG is itself complex due to presence of at least two power converters, increased number of measurements and various transformations used in control algorithm. Inclusion of power angle control strategies, though beneficial in terms of reducing VA ratings, leads to further increase in complexity of control. So, development of a simple power angle control is necessary.

- Exhaustive evaluation of PAC methods in different operating conditions such as unbalance in load and source voltages is missing in existing literature. Unbalance in three phase system can lead to circulation currents when sharing reactive power between series and shunt APFs, which is not taken care of in existing PAC methods.

- Most of the power angle control (PAC) methods of UPQCDG proposed so far are based on IRPT, which makes its performance deteriorate during grid voltage distortions. So, SRFT based PAC methods for UPQCDG are desirable for its robust operation. Though SRFT based PAC methods have been proposed for conventional UPQC, they are inefficient due to inadequacy to support large power angles, and extension of them for UPQCDG also requires considerable modification due to injection of DG power at DC link.

- Based on proper selection of power angle VA loading and rating of UPQCDG can be optimized. Optimum design of UPQCDG based PAC approach considering different operating conditions is missing though such researches have been carried out for conventional UPQC.

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