ANALYSIS OF IUPQC AND ITS APPLICABILTY IN POWER QUALITY COMPENSATION AS WELL AS IN MICROGRID APPLICATIONS

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ABSTRACT

This paper presents an improved controller for the dual topology of the unified power quality conditioner (iUPQC) extending its applicability in power quality compensation, as well as in microgrid applications. By using this controller, beyond the conventional UPQC power quality features, including voltage sag/swell compensation, the iUPQC will also provide reactive power support to regulate not only the load-bus voltage but also the voltage at the grid-side bus. In other words, the iUPQC will work as a static synchronous compensator (STATCOM) at the grid side, while providing also the conventional UPQC compensations at the load or microgrid side. Experimental results are provided to verify the new functionality of the equipment.

I. INTRODUCTION

Certainly power-electronics devices have brought about great technological improvements. However, the increasing number of power-electronics-driven loads used generally in the industry has brought about uncommon power quality problems. In contrast, power-electronics-driven loads generally require ideal sinusoidal supply voltage in order to function properly, whereas they are the most responsible ones for abnormal harmonic currents level in the distribution system. In this scenario, devices that can mitigate these drawbacks have been developed over the years. Some of the solutions involve a flexible compensator, known as the unified power quality conditioner (UPQC) [1]–[7] and the static synchronous compensator (STATCOM) [8]–[13].

The power circuit of a UPQC consists of a combination of a shunt active filter and a series active filter connected in a back-to-back configuration. This combination allows the simultaneous compensation of the load current and the supply voltage, so that the compensated current drawn from the grid and the compensated supply voltage delivered to the load are kept balanced and sinusoidal. The dual topology of the UPQC, i.e., the iUPQC, was presented in [14]–[19], where the shunt active filter behaves as an ac-voltage source and the series one as an ac-current source, both at the fundamental frequency. This is a key point to better design the control gains, as well as to optimize the *LCL* filter of the power converters, which allows improving significantly the overall performance of the compensator [20].

The STATCOM has been used widely in transmission networks to regulate the voltage by means of dynamic reactivepower compensation. Nowadays, the STATCOM is largely used for voltage regulation [9], whereas the UPQC and the iUPQC have been selected as solution for more specific applications [21]. Moreover, these last ones are used only in particular cases, where their relatively high costs are justified by the power quality improvement it can provide, which would be unfeasible by using conventional solutions. By joining the extra functionality like a STATCOM in the iUPQC device, a wider scenario of applications can be reached, particularly in case of distributed generation in smart grids and as the coupling device in grid-tied microgrids.

In [16], the performance of the iUPQC and the UPQC was compared when working as UPQCs. The main difference between these compensators is the sort of source emulated by the series and shunt power converters. In the UPQC approach, the series converter is controlled as a nonsinusoidal voltage source and the shunt one as a nonsinusoidal current source. Hence, in real time, the UPQC controller has to determine and synthesize accurately the harmonic voltage and current to be compensated. On the other hand, in the iUPQC approach, the series converter behaves as a controlled sinusoidal current source and the shunt converter as a controlled sinusoidal voltage source. This means that it is not necessary to determine the harmonic voltage and current to be compensated, since the harmonic voltages appear naturally across the series current source and the harmonic currents flow naturally into the shunt voltage source.

II. CUSTOM POWER DEVICES

Initially for the improvement of power quality or reliability of the system FACTS devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow controller (IPFC), and unified power flow controller (UPFC) etc are introduced. These FACTS devices are designed for the transmission system. But now a day as more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The term —custom power‖ describes the value-added power that electric utilities will offer to their customers. The value addition involves the application of high power electronic controllers to distribution systems, at the supply end of industrial, commercial consumers. The main custom power devices which are used in distribution system for power quality improvement are distribution static synchronous compensator (DSTATCOM), dynamic voltage Restorer (DVR), active filter (AF), unified power quality conditioner (UPQC) etc. N.G Hingorani was the first to propose FACTS controllers for improving PQ. He termed them as Custom Power Devices (CPD). These are based on VSC and are of 3 types given below.

- Shunt connected Distribution STATCOM (DSTATCOM)
- Series connected Dynamic Voltage Restorer (DVR)
- Combined shunt and series, Unified Power Quality Conditioner (UPQC).

The DVR is similar to SSSC while UPQC is similar to UPFC. In spite of the similarities, the control techniques are quite different for improving PQ. A major difference involves the injection of harmonic currents and voltages to separate the source from the load. A DVR can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation. A UPQC can be considered as the combination of DSTATCOM and DVR. A DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation to improve power factor or regulate the load bus voltage. Several power providers have installed custom power devices for mitigating power quality problems. In particular, three major power quality devices (PQDs)—an advanced static VAR compensator, a dynamic voltage restorer, and a high-speed transfer switch are used these days. Over the past ten years, advanced power electronic devices have been the center of various research studies, installation projects, and development technologies. By custom power devices, we refer to power electronic static controllers used for power quality development on distribution systems rated 1 through 38 kV. This interest in the usage of power quality devices (PQDs) arises from the need of mounting power quality levels to meet the everyday growing sensitivity of consumer needs and expectations. Power quality levels, if not achieved, can cause costly downtimes and customer dissatisfaction. According to contingency planning research company's annual study, downtime caused by power disturbances results in major financial losses. In order to face these new needs, advanced power electronic devices have developed over the last years. Their performance has been demonstrated at medium distribution levels, and most are available as commercial products.

III. SYSTEM CONFIGURATION

In order to clarify the applicability of the improved Iupqc controller, Fig depicts an electrical system with two buses in spotlight, i.e., bus A and bus B. Bus A is a critical bus of the power system that supplies sensitive loads and serves as point of coupling of a microgrid. Bus B is a bus of the microgrid, where nonlinear loads are connected, which requires premium-quality power supply. The voltages at buses A and B must be regulated, in order to properly supply the sensitive loads and the nonlinear loads. The effects caused by the harmonic currents drawn by the nonlinear loads should be mitigated, avoiding harmonic voltage propagation to bus A. The use of a STATCOM to guarantee the voltage regulation at bus A is not enough because the harmonic currents drawn by the nonlinear loads are not mitigated. On the other hand, a UPQC or an iUPQC between bus A and bus B can compensate the harmonic currents of the nonlinear loads and compensate the voltage at bus B, in terms of voltage harmonics, unbalance, and sag/swell. Nevertheless, this is still not enough to guarantee the voltage regulation at bus A. Hence, to achieve all the desired goals, a STATCOM at bus A and a UPQC (or an iUPQC) between buses A and B should be employed. However, the costs of this solution would be unreasonably high. An attractive solution would be the use of a modified iUPQC controller to provide also reactive power support to bus A, in addition to all those functionalities of this equipment, as presented in [16] and [18]. Note that the modified iUPQC serves as an intertie between buses A and B. Moreover, the microgrid connected to the bus B could be a complex system comprising distributed generation, energy management system, and other control systems involving microgrid, as well as smart grid concepts [22].

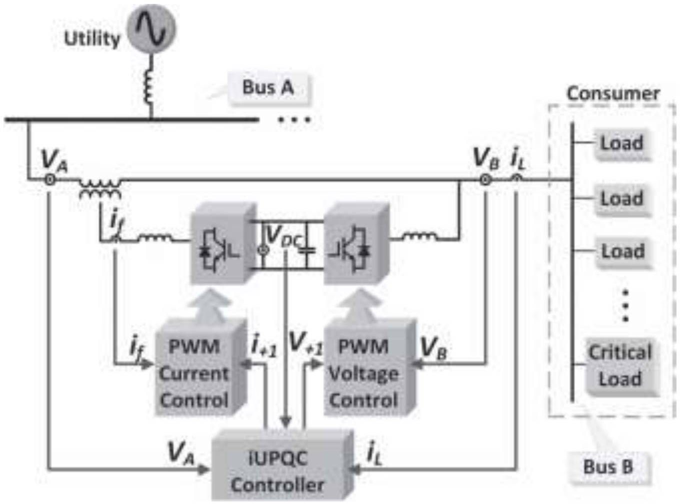

Fig.1. Modified iUPQC configuration

In summary, the modified iUPQC can provide the following functionalities:
a) "smart" circuit breaker as an intertie between the grid and the microgrid;
b) energy and power flow control between the grid and the microgrid (imposed by a tertiary control layer for the microgrid);
c) reactive power support at bus A of the power system;
d) voltage/frequency support at bus B of the microgrid;
e) harmonic voltage and current isolation between bus A and bus B (simultaneous grid-voltage and load-current activefiltering capability);
f) voltage and current imbalance compensation. The functionalities (d)–(f) previously listed were extensively explained and verified through simulations and experimental analysis [14]–[18], whereas the functionality (c) comprises the original contribution of the present work. Fig.5.1 depicts, in detail, the connections and measurements of the iUPQC
between bus A and bus B. According to the conventional iUPQC controller, the shunt converter imposes a controlled sinusoidal voltage at bus B, which corresponds to the aforementioned functionality (d). As a result, the shunt converter has no further degree of freedom in terms of compensating active- or reactive-power variables to expand its functionality. On the other hand, the series converter of a conventional iUPQC uses only an active-power control variable *p*, in order to synthesize a fundamental sinusoidal current drawn from bus A, corresponding to the active power demanded by bus B. If the dc link of the iUPQC has no large energy storage system or even no energy source, the control variable *p* also serves as an additional active-power reference to the series converter to keep the energy inside the dc link of the iUPQC balanced. In this case, the losses in the iUPQC and the active power supplied by the shunt converter must be quickly compensated in the form of an additional active power injected by the series converter into the bus B. The iUPQC can serve as: a) "smart" circuit breaker and as b) power flow controller between the grid and the microgrid only if the compensating active- and reactive-power references of the series converter can be set arbitrarily. In this case, it is necessary to provide an energy source (or large energy storage) associated to the dc link of the iUPQC. The last degree of freedom is represented by a reactive-power control variable *q* for the series converter of the iUPQC. In this way, the iUPQC will provide reactive-power compensation like a STATCOM to the bus A of

the grid. As it will be confirmed, this functionality can be added into the controller without degrading all other functionalities of the iUPQC.

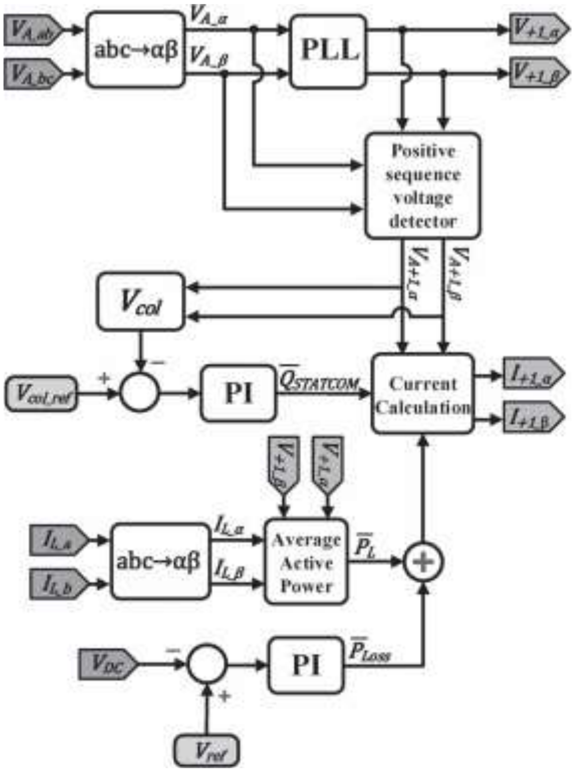

Fig. 2. Novel iUPQC controller.

IV. IMPROVED IUPQC CONTROLLER

Main Controller

The controller inputs are the voltages at buses A and B, the current demanded by bus B (*iL*), and the voltage *v*DC of the common dc link. The outputs are the shunt-voltage reference and the series-current reference to the pulse width modulation (PWM) controllers. The voltage and current PWM controllers can be as simple as those employed in [18], or be improved further to better deal with voltage and current imbalance and harmonics [23]–[28]. First, the simplified Clark transformation is applied to the measured variables. As example of this transformation, the grid voltage in the *αβ*-reference frame can be calculated as

$$\begin{bmatrix} V_{A\_\alpha} \\ V_{A\_\beta} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{A\_ab} \\ V_{A\_bc} \end{bmatrix}. \qquad (1)$$

The shunt converter imposes the voltage at bus B. Thus, it is necessary to synthesize sinusoidal voltages with nominal amplitude and frequency. Consequently, the signals sent to the PWM controller are the phase-locked loop (PLL) outputs with amplitude equal to 1 p.u. There are many possible PLL algorithms, which could be used in this case, as verified in [29]–[33].

In the original iUPQC approach as presented in [14], the shunt-converter voltage reference can be either the PLL outputs or the fundamental positive-sequence component *VA*+1 of the

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grid voltage. The use of *VA*+1 in the controller is useful to minimize the circulating power through the series and shunt converters, under normal operation, while the amplitude of the grid voltage is within an acceptable range of magnitude. However, this is not the case here, in the modified iUPQC controller, since now the grid voltage will be also regulated by the modified iUPQC. In other words, both buses will be regulated independently to track their reference values. The series converter synthesizes the current drawn from the grid bus (bus A). In the original approach of iUPQC, this current is calculated through the average active power required
by the loads *PL* plus the power *P*Loss. The load active power can be estimated by

$$P_L = V_{+1\_\alpha} \cdot i_{L\_\alpha} + V_{+1\_\beta} \cdot i_{L\_\beta} \qquad (2)$$

where *iL_α*, *iL_β* are the load currents, and *V*+1_*α*, *V*+1_*β* are the voltage references for the shunt converter. A low-pass filter is used to obtain the average active power (*PL*). The losses in the power converters and the circulating power to provide energy balance inside the iUPQC are calculated indirectly from the measurement of the dc-link voltage. In other words, the power signal *P*Loss is determined by a proportional integral (PI) controller, by comparing the measured dc voltage *V*DC with its reference value. The additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal *Q*STATCOM . This control signal is obtained through a PI controller, in which the input variable is the error between the reference value and the actual aggregate voltage of the grid bus, given by

$$|V_{\text{col}} = \sqrt{V_{A+1\_\alpha}^2 + V_{A+1\_\beta}^2}. \qquad (3)$$

The sum of the power signals *PL* and *P*Loss composes the active-power control variable for the series converter of the iUPQC (*p*) described in Section II. Likewise, *Q*STATCOM is the reactive-power control variable *q*. Thus, the current references *i*+1*α* and *i*+1*β* of the series converter are determined by

$$\begin{bmatrix} i_{+1\_\alpha} \\ i_{+1\_\beta} \end{bmatrix} = \frac{1}{V_{A+1\_\alpha}^2 + V_{A+1\_\beta}^2} \begin{bmatrix} V_{A+1\_\alpha} & V_{A+1\_\beta} \\ V_{A+1\_\beta} & -V_{A+1\_\alpha} \end{bmatrix} \times \begin{bmatrix} \overline{P}_L + \overline{P}_{\text{Loss}} \\ \overline{Q}_{\text{STATCOM}} \end{bmatrix}. \qquad (4)$$

Power Flow in Steady State

The following procedure, based on the average power flow, is useful for estimating the power ratings of the iUPQC converters. For combined series–shunt power conditioners, such as the UPQC and the iUPQC, only the voltage sag/swell disturbance and the power factor (PF) compensation of the load produce a circulating average power through the power conditioners [34], [35], the compensation of a voltage sag/swell disturbance at bus B causes a positive sequence voltage at the coupling transformer (*V*series _= 0), since *VA* _= *VB*. Moreover, *V*series and *iPB* in the coupling transformer leads to a circulating active power *P* inner in the iUPQC. Additionally, the compensation of the load PF increases the current supplied by the shunt converter. The following analysis is valid for an iUPQC acting like a conventional UPQC or including the extra compensation like a STATCOM. First, the circulating power will be calculated when the iUPQC is operating just like a conventional UPQC. Afterward, the equations will include the STATCOM functionality to the grid bus A. In both cases, it will be assumed that the iUPQC controller is able to force the shunt converter of the iUPQC to generate fundamental voltage always in phase with the grid voltage at bus A. For simplicity, the losses in the iUPQC will be neglected.

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V. SIMULATION RESULTS

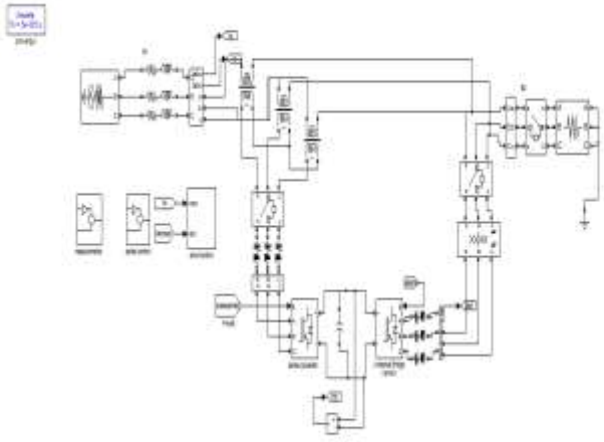
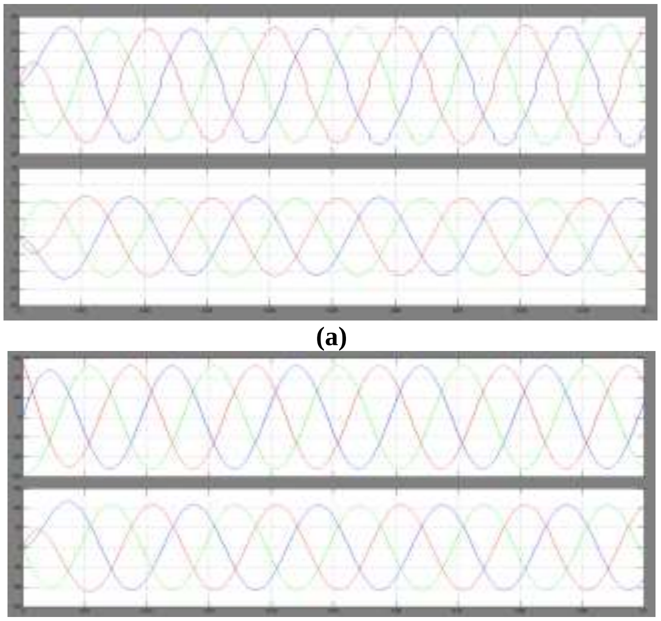


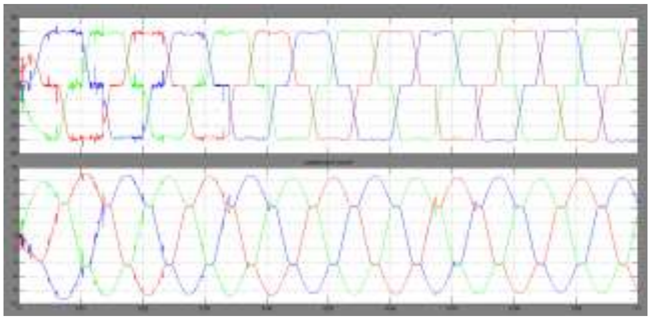
Fig 3 Matlab/simulink diagram of modified IUPQC



(a)

(b)

Fig 4 iUPQC response at no load condition: (a)Load current and compensated current (b)Grid voltages and currents



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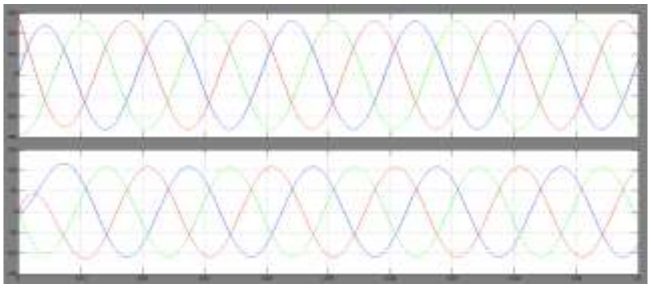
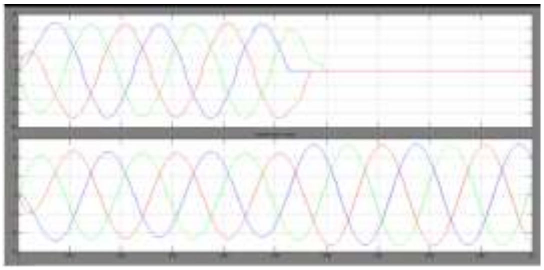
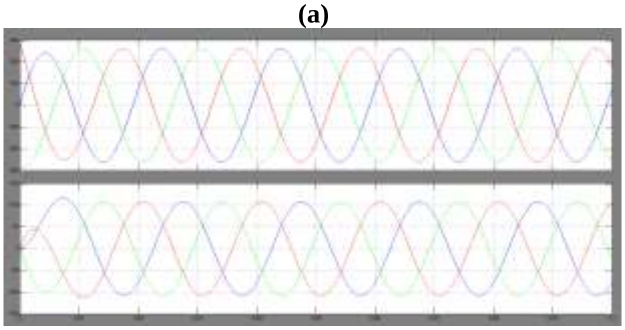


(b)

Fig 7.3 iUPQC transitory response during the connection of a three phase diode rectifier: (a)Load current and compensated current (b)Grid voltages and currents



(a)



(b)

Fig. 7.4. iUPQC transitory response during the connection of a twophase diode rectifier: (a)Load current and compensated current (b)Grid voltages and currents

VI. CONCLUSION

In the improved iUPQC controller, the currents synthesized by the series converter are determined by the average active power of the load and the active power to provide the dc-link voltage regulation, together with an average reactive power to regulate the grid-bus voltage. In this manner, in addition to all the power-quality compensation features of a conventional UPQC or an iUPQC, this improved controller also mimics a STATCOM to the grid bus. This new feature enhances the applicability of the iUPQC and provides new solutions in future scenarios involving smart grids and microgrids, including distributed generation and energy storage systems to better deal with the inherent variability of renewable resources such as solar and wind power. Moreover, the improved iUPQC controller may justify the costs and promotes the iUPQC applicability in power quality issues of critical systems, where it is necessary not only an iUPQC or a STATCOM, but both, simultaneously. Despite the addition of one more power-quality compensation feature, the grid-voltage regulation reduces the inner-loop circulating power inside the iUPQC, which would allow lower power rating for the series converter. The simulation results verified the improved iUPQC goals. The grid-voltage regulation was achieved with no load, as well as when supplying a three-phase nonlinear load. These results have demonstrated a suitable performance of voltage regulation at both sides of the iUPQC, even while compensating harmonic current and voltage imbalances.

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