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Enhancement of Power Quality of Power Distribution System Using Modified iUPQC Controller

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ABSTRACT

This project 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. Power quality has become an important factor in power systems, for consumer and household appliances with proliferation of various electric and electronic equipment and computer systems. The main causes of a poor power quality are harmonic currents, poor power factor, supply-voltage variations, etc. A technique of achieving both active current distortion compensation, power factor correction and also mitigating the supply-voltage variation at the load side, is compensated by unique device of iUPQC and a modified synchronous-reference frame based control method to Shunt active filter and instantaneous power quality theory based control technique for series active filter to compensate power-quality problems. By using this controller, beyond the conventional UPQC power quality features, including voltage sag and 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.

Index Terms - ***iUPQC, microgrids, power quality, static synchronous compensator (STATCOM), unified power quality conditioner (UPQC).***

INTRODUCTION

The modem power distribution system is becoming highly vulnerable to the different power quality problems. The extensive use of non-linear loads is further contributing to increased current and voltage harmonics issues. Furthermore, the penetration level of small and large scale renewable energy systems based on wind energy, solar energy, fuel cell, etc., installed at distribution as well as transmission levels is increasing significantly. Unified power quality control was widely studied by many researchers as an eventual method to improve power quality of electrical distribution system. The function of unified power quality conditioner is to compensate supply voltage flicker/imbalance, reactive power, negative sequence current, and harmonics.

In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. Therefore, the UPQC is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance. The UPQC consisting of the combination of a series active power filter (APF) and shunt active power filter (APF) can also compensate the voltage interruption if it has some energy storage or battery in the dc link. The shunt APF is usually connected across the loads to compensate for all current related problems such as the reactive power compensation, power factor improvement, current harmonic, compensation, and load unbalance compensation whereas the series APF is connected in a series with the line through series transformers. It acts as controlled voltage source and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc.

The proposed control technique has been evaluated and tested under non-ideal mains voltage and unbalanced load conditions using Matlab/Simulink software. The proposed method is also validated through experimental study. The following diagram shows the generalized UPQC system. The UPQC consists of two voltage source inverters Connected back to back with each of them sharing a common dc link. One inverter work as a variable voltage source is called series APF, and the other as a variable current source in called shunt APF. The main aim of the series APF is harmonic isolation between load and Supply, it has the capability of voltage flicker/ imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer PCC. The shunt APF is used to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc link voltage between both APFs.

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, 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.

The STATCOM has been used widely in transmission networks to regulate the voltage by means of dynamic reactive power compensation. Nowadays, the STATCOM is largely used for voltage regulation, whereas the UPQC and the iUPQC have been selected as solution for more specific applications. 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 micrograms.

SYSTEM CONFIGURATION

The general iUPQC will be installed at substations by electric power utilities in the near future. The integration of the series-active and shunt-active filters is called the UPQC, associated with the unified power flow controller which has been proposed by Gyugyi. However, the UPQC for distribution systems is quite different. The aim of the specific UPQC is not only to compensate for the current harmonics produced by a 12-pulse thyristor rectifier of 20 kVA, but also to eliminate the voltage flicker/imbalance contained in the receiving terminal voltage from the load terminal voltage The receiving terminal is often corresponding to the utility-consumer point of common coupling in high-power applications. The UPQC consists of a 1.5-

kVA series-active filter and a 0.5-kVA shunt-active filter. The dc links of both active filters are connected to a common dc capacitor of 2000 F. The 12-pulse thyristor bridge rectifier is considered a voltage-flicker/imbalance-sensitive load identical to a dc power supply for super-conductive material tests.

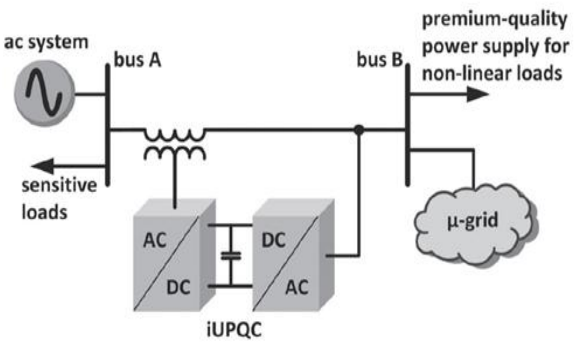

Fig. 1 General iUPQC

The power circuit of the 1.5-kVA series-active filter consists of three single-phase H-bridge voltage-fed pulse-width-modulation (PWM) inverters using four insulated gate bipolar transistors (IGBT's) in each phase. The operation of the series-active filter greatly forces all the current harmonics produced by the thyristor rectifier into an existing shunt-passive filter of 10 kVA. It also has the capability of damping series/parallel resonance between the supply impedance and the shunt-passive filter. The 0.5-kVA shunt-active filter consisting of a three-phase voltage-fed PWM inverter is connected in parallel to the supply by a step-up transformer. The only objective of the shunt-active filter is to regulate the dc-link voltage between both active filters.

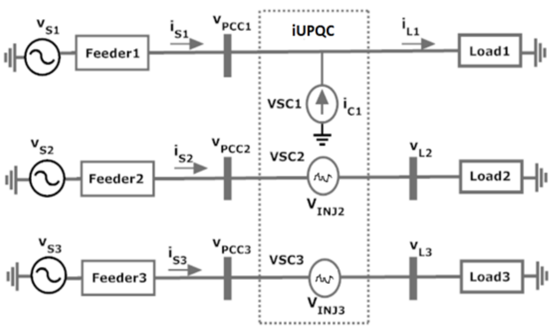

Fig. 2 System configuration of iUPQC

With the development in the process control and digital electronics communications, a number of sensitive critical loads which require sinusoidal supply voltage for their proper operation are extensively used. It is well established by the application of custom power controllers in distribution sector that power quality can be significantly improved. A unified power quality conditioner (UPQC) which integrates a series and a shunt active power filters is used to mitigate voltage and current imperfections in a distribution feeder. The shunt compensator of UPQC compensate for load current related problems such as current harmonic unbalance, power factor correction and reactive power required by the load while the series compensator can compensate for all voltage related problems such as voltage sag/swell, voltage harmonics etc.

Many researchers have shown that UPQC as a versatile device to improve the power quality in distribution systems. A novel power quality conditioner for three-feeder distribution systems, called as UPQC which is realized by three single-phase three-level VSCs connected back-to-back by a common dc link capacitor. One VSC is connected in shunt to a feeder through a coupling transformer and the other two VSCs, each in series with a feeder, are connected to the other two feeders through injection transformers. As there is no published work on the UPQC, it is essential to establish the validity of its compensation performance in distribution or industrial networks. A new controller strategy based on synchronous reference frame for series compensators is also proposed. Essentially the proposed iUPQC accomplishes the following:

- The shunt VSC compensates current harmonics and reactive power required by one feeder. It also supports the real power required by the other two VSCs and regulates the voltage of dc link capacitor.

- The two series VSCs mitigates voltage waveform distortion, voltage sag/swell and interruptions (protect the sensitive loads

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connected to the other two feeders against voltage imperfections).

Static Synchronous Compensator (STATCOM)

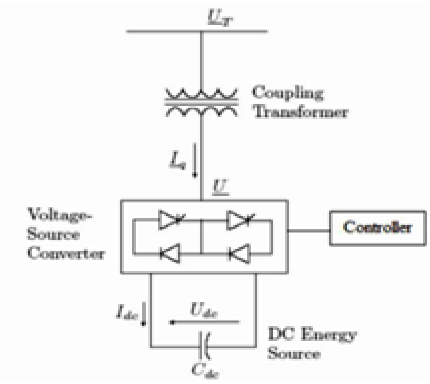

Fig. 3 Structure of a STATCOM

Basically, STATCOM is comprised of three main parts are, a voltage source converter (VSC), a step-up coupling transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters.

A. Control of STATCOM: The controller of a STATCOM operates the converter in a particular way that the phase angle between the converter voltage and the transmission line voltage is dynamically adjusted and synchronized so that the STATCOM generates or absorbs desired VAR at the point of coupling connection.

The STATCOM with a converter voltage source _1*E* and a tie connected to a system with a voltage source, and a Thevenin's reactance, XTIEX_THV$_{TH}$.

B. Operating Principles Of STATCOM: The STATCOM is connected to the power system at a PCC (point of common coupling), through a step-up coupling transformer, where the voltage-quality problem is a concern. The PCC is also known as the terminal for which the terminal voltage is U_T.

All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals (firing angle) to drive the main semiconductor switches of the power converter accordingly to either increase the voltage or to decrease it accordingly. A STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks.

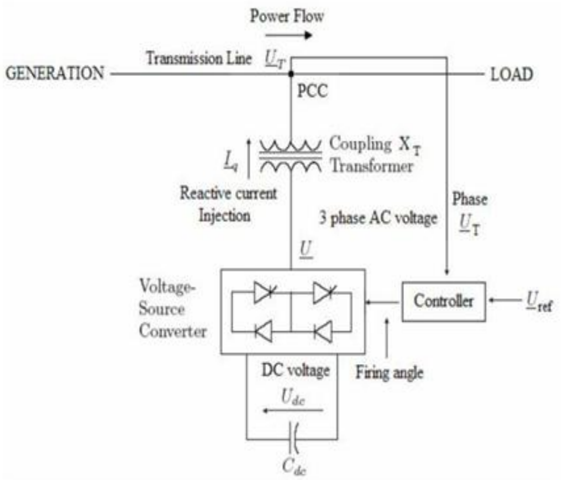

Fig. 4 STATCOM operation in a power system

The charged capacitor C_{dc} provides a DC voltage, U_{dc} to the converter, which produces a set of controllable three-phase output voltages, U in synchronism with the AC system. The synchronism of the three-phase output voltage with the transmission line voltage has to be performed by an external controller. The amount of desired voltage across STATCOM, which is the voltage reference, Uref, is set manually to the controller. The voltage control is there by to match UT with Uref which has been elaborated. This matching of voltages is done by varying the amplitude of the output voltage U, which is done by the firing angle set by the controller. The controller thus sets UT equivalent to the Uref.

The reactive power exchange between the converter and the AC system can also be controlled. This reactive power exchange is the reactive current injected by the STATCOM, which is the current from the capacitor produced by absorbing real power from the AC system.

iUPQC CONTROLLER

In order to clarify the applicability of the improved iUPQC controller, 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. 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.

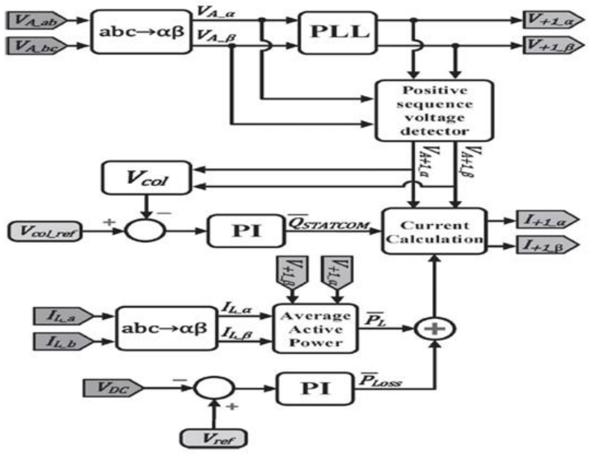

Fig. 5 Control algorithm of iUPQC Controller

In summary, the modified iUPQC can provide the following functionalities:

- "smart" circuit breaker as an intertie between the grid and the microgrid;
- energy and power flow control between the grid and the microgrid (imposed by a tertiary control layer for the microgrid);
- reactive power support at bus A of the power system;
- voltage/frequency support at bus B of the microgrid;
- harmonic voltage and current isolation between bus A and bus B (simultaneous grid-voltage and load-current active-filtering capability);
- voltage and current imbalance compensation.

According to the conventional iUPQC controller, the shunt converter imposes a controlled sinusoidal voltage at bus B, which corresponds to the aforementioned functionality. 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.

First, the simplified Clark transformation is applied to the measured variables. As example of this transformation, the grid voltage in the $\alpha\beta$-reference frame can be calculated as

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

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 P_L plus the power P_{Loss}. The load active power can be estimated by,

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

where i_{L_α}, i_{L_β} are the load currents, and V_{+1_α}, V_{+1_β} are the voltage references for the shunt converter.

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, —

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

The sum of power signals P_L and P_{LOSS} composes the active power control variable for the series converter of the iUPQC. Likewise, $Q_{STATCOM}$ is the reactive power control variable. Thus the current references i_{+1_α} and i_{+1_β} of the series converter are determined by,

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

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.

The compensation of a voltage sag/swell disturbance at bus B causes a positive-sequence voltage at the coupling transformer ($V_{series} \neq 0$), since VA ≠ VB . Moreover, V_{series} and i_{Pb} in the coupling transformer leads to a circulating active power P $_{inner}$ in the iUPQC.

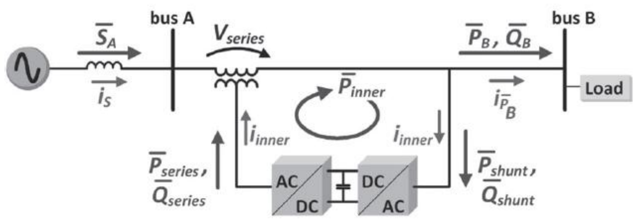

Fig. 6 iUPQC power flow in steady state

For the first case, the following average powers in steady state can be determined,

$$\overline{S}_A = \overline{P}_B \qquad (5)$$
$$\overline{Q}_{shunt} = -\overline{Q}_B \qquad (6)$$
$$\overline{Q}_{series} = \overline{Q}_A = 0 \text{ var} \qquad (7)$$
$$\overline{P}_{series} = \overline{P}_{shunt} \qquad (8)$$

where S_A and Q_A are the apparent and reactive power injected in the bus A, P_B and Q_B are the active and reactive power injected in the bus B, P_{shunt} and Q_{shunt} are the active and reactive power drained by the shunt converter, P_{series} and Q_{series} are the active and reactive power supplied by the series converter, respectively.

If a voltage sag or swell occurs, P_{series} and P_{shunt} will not be zero, and thus, an inner loop current (i_{inner}) will appear. The series and shunt converters and the aforementioned circulating active power (P_{inner}) flow inside the equipment. It is convenient to define the following sag/swell factor. Considering V_N as the nominal voltage

$$k_{sag/swell} = \frac{|\dot{V}_A|}{|\dot{V}_N|} = \frac{V_A}{V_N}. \qquad (9)$$

From (5) and considering that the voltage at bus B is kept regulated, i.e., $V_B = V_N$, it follows that

$$\sqrt{3} \cdot k_{sag/swell} \cdot V_N \cdot i_S = \sqrt{3} \cdot V_N \cdot i_{P_B}$$
$$i_S = \frac{i_{P_B}}{k_{sag/swell}} = i_{\overline{P}_B} + i_{inner} \qquad (10)$$

$$i_{\text{inner}} = \left| i_{P_B} \left(\frac{1}{K_{\text{sag/swell}} - 1} \right) \right|. \quad (11)$$

The circulating power is given by

$$\overline{P}_{\text{inner}} = \overline{P}_{\text{series}} = \overline{P}_{\text{shunt}} = 3(V_B - V_A)(i_{P_B} + i_{\text{inner}}). \quad (12)$$

From (11) and (12), it follows that

$$\overline{P}_{\text{inner}} = 3(V_N - V_A)\left(\frac{\overline{P}_B}{3V_N} \frac{1}{k_{\text{sag/swell}}} \right) \quad (13)$$

$$\overline{P}_{\text{inner}} = \overline{P}_{\text{series}} = \overline{P}_{\text{shunt}} = \frac{1 - K_{\text{sag/swell}}}{k_{\text{sag/swell}}} \overline{P}_B. \quad (14)$$

Thus, (14) demonstrates that P_{inner} depends on the active power of the load and the sag/swell voltage disturbance. In order to verify the effect on the power rate of the series and shunt converters, a full load system 1 p.u. with PF ranging from 0 to 1 was considered. It was also considered the sag/swell voltage disturbance at bus A ranging $k_{sag/swell}$ from 0.5 to 1.5. In this way, the power rating of the series and shunt converters are obtained through (6)–(8) and (14).

If the iUPQC performs all original UPQC functionalities together with the STATCOM functionality, the voltage at bus A is also regulated with the same phase and magnitude, that is, $\dot{V}_A = \dot{V}_B = \dot{V}_N$, and then, the positive sequence of the voltage at the coupling transformer is zero ($V_{series} = 0$). Thus, in, steady state, the power flow is determined by,

$$\overline{S}_A = \overline{P}_B + \overline{Q}_{\text{STATCOM}} \quad (15)$$

$$\overline{Q}_{\text{STATCOM}} + \overline{Q}_{\text{series}} = \overline{Q}_{\text{shunt}} + \overline{Q}_B \quad (16)$$

$$\overline{Q}_{\text{series}} = 0 \text{ var} \quad (17)$$

$$\overline{P}_{\text{series}} = \overline{P}_{\text{inner}} = 0 \text{ W} \quad (18)$$

where $Q_{STATCOM}$ is the reactive power that provides voltage regulation at bus A. Ideally, the STATCOM functionality mitigates the inner-loop active power flow (P_{inner}), and the power flow in the series converter is zero. Consequently, if the series converter is properly designed along with the coupling transformer to synthesize the controlled currents I_{+1_α} and I_{+1_β} , as shown in Fig. 3, then a lower power converter can be employed. Contrarily, the shunt converter still has to provide the full reactive power of the load and also to drain the reactive power injected by the series converter to regulate the voltage at bus A.

Experimental Results

The improved iUPQC controller, was verified in a 5-KVA prototype, whose parameters are presented below. The controller was embedded in a fixed-point digital signal processor (TMS320F2812). In order to verify all the power quality issues described in this project, the iUPQC was connected to a grid with a voltage sag system. The voltage sag system was composed by an inductor (L_S), a resistor (R_{rmSag}), and a breaker (S_{Sag}). To cause a voltage sag at bus A, S_{Sag} is closed.

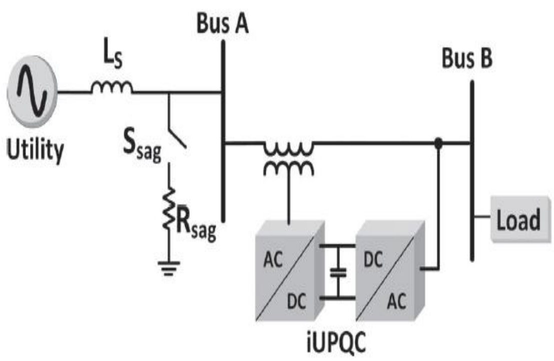

Fig. 7 iUPQC experimental scheme

At first, the source voltage regulation was tested with no load connected to bus B. In this case, the iUPQC behaves as a STATCOM, and the breaker S_{Sag} is closed to cause the voltage sag. To verify the grid-voltage regulation, the control of the $Q_{STATCOM}$ variable is enabled to compose (4) at instant t = 0 s. In this experimental case, LS = 10 mH, and R_{Sag} = 7.5 Ω. Before the $Q_{STATCOM}$ variable is enabled, only the dc link and the voltage at bus B are regulated, and there is a voltage sag at bus A, After t = 0 s, the iUPQC starts to draw reactive current from bus A, increasing the voltage until its reference value. The load voltage at

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bus B is maintained regulated during all the time, and the grid-voltage regulation of bus A has a fast response. Next, the experimental case was carried out to verify the iUPQC performance during the connection of a nonlinear load with the iUPQC already in operation.

The load is a three-phase diode rectifier with a series RL load at the dc link (R = 45 Ω and L = 22 mH), and the circuit breaker S_{Sag} is permanently closed, with a L_S = 10 mH and a R_{Sag} = 15 Ω. In this way, the voltage-sag disturbance is increased due to the load connection. It is possible to verify that the iUPQC is able to regulate the voltages at both sides of the iUPQC, simultaneously.

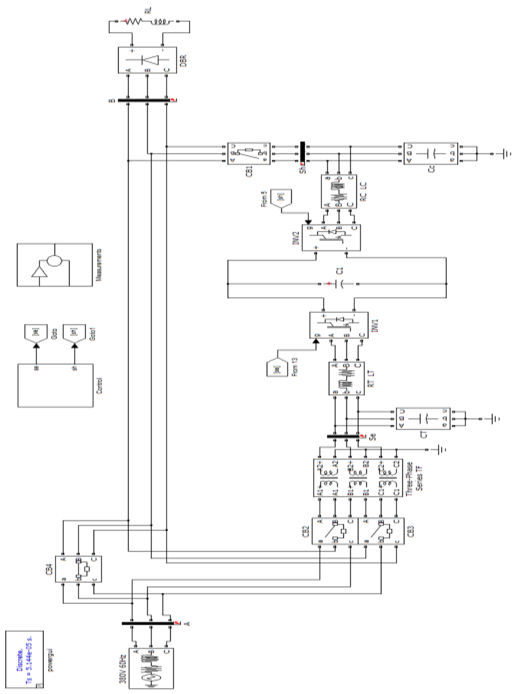

Fig. 8 Simulation circuit

Even after the load connection, at t = 0 s, the voltages are still regulated, and the currents drawn from bus A are almost sinusoidal. Hence, the iUPQC can perform all the power-quality compensations, as mentioned before, including the grid-voltage regulation. It is important to highlight that the grid-voltage regulation is also achieved by means of the improved iUPQC controller.

TABLE I
iUPQC PROTOTYPE PARAMETERS

Parameter	Value
Voltage	220 V rms
Grid frequency	60 Hz
Power rate	5 kVA
DC-link voltage	450 V dc
DC-link capacitors	C = 9400 µF
Shunt converter passive filter	L = 750 µH R = 3.7 Ω C = 20.0 µF
Series converter passive filter	L = 1.0 mH R = 7.5 Ω C = 20.0 µF
Sampling frequency	19440 Hz
Switching frequency	9720 Hz
PI controller ($\bar{P}_{loss}$)	Kp = 4.0 Ki = 250.0
PI controller ($\bar{Q}_{STATCOM}$)	Kp = 0.5 Ki = 50.0

Finally, the same procedure was performed with the connection of a two-phase diode rectifier, in order to better verify the mitigation of power quality issues. The diode rectifier has the same dc load (R = 45 Ω and L = 22 mH) and the same voltage sag (LS = 10 mH and R_{rmSag} = 15 Ω). Fig. 9 depicts the transitory response of the load connection. Despite the two-phase load currents, after the load connection at t = 0 s, the three-phase current drained from the grid has a reduced unbalanced component. Likewise, the unbalance in the voltage at bus A is negligible.

Unfortunately, the voltage at bus B has higher unbalance content. These components could be mitigated if the shunt compensator works as an ideal voltage source, i.e., if the filter inductor could be eliminated. In this case, the unbalanced current of the load could be supplied by the shunt converter, and the voltage at the bus B could be exactly the voltage synthesized by the shunt converter. Therefore, without filter inductor, there would be no unbalance voltage drop in it and the voltage at bus B would remain balanced. However, in a practical case, this inductor cannot be eliminated, and an improved PWM control to compensate voltage unbalances.

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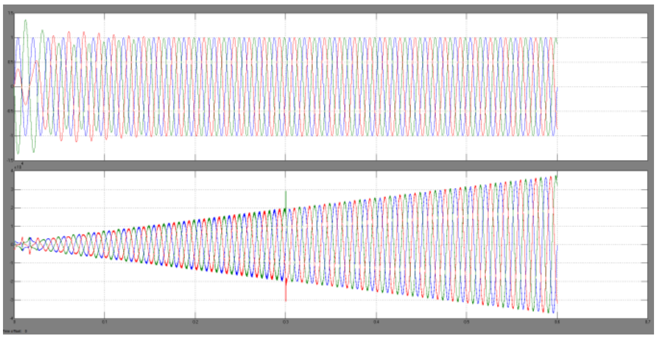

Fig. 9 Controlled outputs of iUPQC

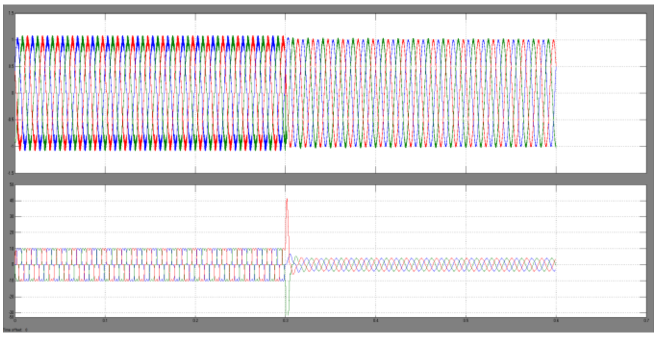

Fig. 10 Measured outputs of iUPQC

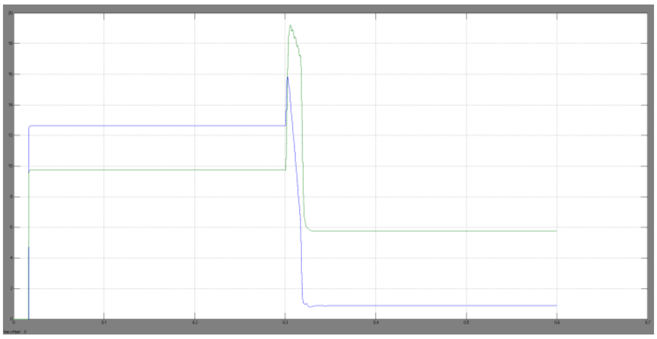

Fig. 11 Three phase positive sequence Active & Reactive power outputs

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 fu-ture 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 experimental 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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