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A Mechanism to Increase the Power Quality of Power Distribution System Using Modified iUPQC Controller



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Abstract

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) and the static synchronous compensator (STATCOM).

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 general UPQC will be installed at sub-stations by electric power utilities in the near future. The main purpose of the series-active filter is harmonic isolation between a sub-transmission system and a distribution system. In addition, the series-active filter has the capability of voltage-flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). The main purpose of the shunt-active filter is to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc-link voltage between both active filters.

Certainly, power-electronics devices have brought about great technological improvements. However, the increasing number of power-electronic-driven loads used generally in the industry has brought about uncommon power-quality problems. In contrast, power-electronic-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) and the static synchronous compensator (STATCOM).

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 microgrids.

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 non-sinusoidal voltage source and the shunt one as a non-sinusoidal 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.

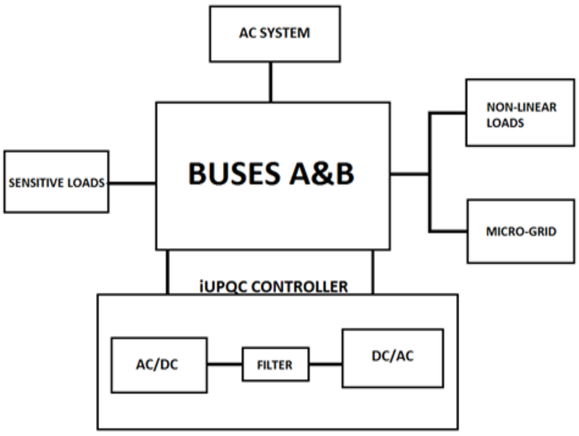

Fig. 1 Block Diagram of iUPQC Controller

In actual power converters, as the switching frequency increases, the power rate capability is reduced. Therefore, the iUPQC offers better solutions if compared with the UPQC in case of high-power applications, since the iUPQC compensating references are pure sinusoidal waveforms at the fundamental frequency. Moreover, the UPQC has higher switching losses due to its higher switching frequency.

An improved controller, which expands the iUPQC functionalities. This improved version of iUPQC controller includes all functionalities of those previous ones, including the voltage regulation at the load-side bus, and now providing also voltage regulation at the grid-side bus, like a STATCOM to the grid. Experimental results are provided to validate the new controller design.

General structure of iUPQC :

The general iUPQC will be installed at substations by electric power utilities in the near future. The main purpose of the series-active filter is harmonic isolation between a sub-transmission system and a distribution system. In addition, the series-active filter has the capability of voltage-flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). The main purpose of the shunt-active filter is to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc-link voltage between both active filters.

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.

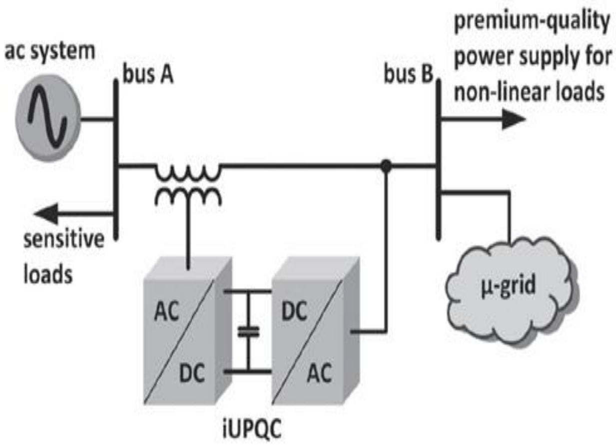

Fig. 2.1 General iUPQC

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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. Thus, the dc link is kept as a constant voltage even when a large amount of active power is flowing into or out of the series-active filter during the flicker compensation. Although the shunt-active filter has the capability of reactive power compensation, the shunt-active filter provides no reactive power compensation in order to achieve the minimum required rating of the shunt-active filter.

The circuit constants of the 10-kVA shunt-passive filter and the filter consists of 5th- and 7th-tuned filters and a high-pass filter for the purpose of harmonic compensation of the 20-kVA 12-pulse thyristor rectifier. The 12-pulse thyristor rectifier practically produces a non-negligible amount of 5th- and 7th-order harmonic currents, not only due to an error or imbalance in the firing angle between the two six-pulse thyristor rectifiers, but also due to a mismatch in the leakage inductance and/or the turn ratio between the two three-phase transformers interfacing the upper and lower rectifiers to the utility. The 5th- and 7th-order harmonic currents amplified as a result of resonance between the supply inductance and the passive filter would flow upstream of the PCC if neither 5th- nor 7th-tuned filter were installed. To damp the harmonic amplification caused by the resonance, 5th- and/or 7th-tuned filters are commonly installed in large-capacity 12-pulse thyristor rectifiers.

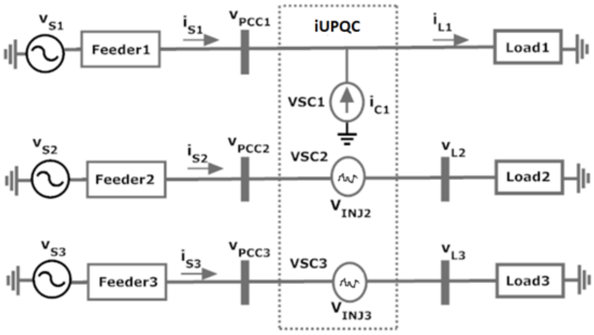

Fig. 2.2 Experimental system configuration of iUPQC

There is a notable difference in the installation point of the shunt-active filter. The reason is clarified as follows, the shunt-active filter compensates for all the current harmonics produced by nonlinear loads downstream of the PCC. Therefore, it should be connected downstream of the series-active filter acting as a high resistor for harmonic frequencies. In the shunt-active filter draws or injects the active power fluctuating at a low frequency from or into the supply, while the existing shunt-passive filter absorbs the current harmonics. To avoid interference between the shunt-active and passive filters, the shunt-active filter should be connected upstream of the series-active filter. A three-phase voltage-fed PWM inverter connected in series with the supply is used as a voltage-flicker/imbalance generator in this experiment.

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. At the same time increased use of nonlinear loads by both electric utilities and end users has been affecting the quality of electric power, by causing major power quality disturbances in the distribution system such as voltage and current harmonics, imbalances, voltage flicker, voltage sag/swell and voltage interruptions etc. As such improvement of power quality in distribution systems is a major issue for utilities. 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 flexible alternative current transmission system (FACTS) controller called as a improved unified power flow controller (UPFC) consisting of three or more VSCs, one connected in shunt and the other two or more VSCs connected in series with transmission lines capable of simultaneous control of the bus voltage of one line and independent active and reactive power flows of other transmission lines is employed as published in the last decade. Based on the application in transmission system the concept of UPFC can be extended to distribution systems. At recent times most of research work on distribution FACTS controllers has been centered on utilizing of two back-to-back VSCs. An interline unified power quality conditioner (IUPQC) consisting of two VSCs, one in shunt to regulate the bus voltage of one feeder and the other in series to regulate the voltage across a sensitive load of the other feeder is proposed in. A multi-converter unified power quality conditioner (MC-UPQC) having three VSCs connected back-to-back by a dc link is reported to compensate both current and voltage imperfections in one feeder and voltage imperfections in another feeder.

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 connected to the other two feeders against voltage imperfections).

Existing system

In this configuration the series active filter is voltage controlled in order to compensate the grid distortion, allowing the load voltage to be consisted only by the fundamental content. This way, the voltage compensated by the series active filter is composed by a fundamental content in order to compensate the sags/swells and the voltage unbalance, and by the harmonics, the same harmonics which are intended to compensate from the grid voltage, 180o phase shifted. The parallel filter is current controlled and it is responsible for draining the load current complementary harmonic contents, allowing a sinusoidal grid current. The parallel filter may still drain a fundamental content in order to compensate the load displacement power factor. The series filter connection to the utility grid is made through a transformer, while the parallel filter is most of the time connected directly to the load connection, in low voltage grid applications.

Proposed system

This paper proposes an improved controller, which expands the iUPQC functionalities. This improved version of iUPQC controller includes all functionalities of those previous ones, including the

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voltage regulation at the load-side bus, and now providing also voltage regulation at the grid-side bus, like a STATCOM to the grid.

Advantages

- Compensating harmonic current and voltage imbalances.

Applications

- Distributed generation and energy storage systems.
- Renewable resources such as solar and wind power.

Static Synchronous Compensator (STATCOM) :

The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. In addition, in the event of a rapid change in system voltage, the capacitor voltage does not change instantaneously; therefore, STATCOM effectively reacts for the desired responses. For example, if the system voltage drops for any reason, there is a tendency for STATCOM to inject capacitive power to support the dipped voltages.

STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM. These advantages compared to other shunt compensators include:

- Size, weight, and cost reduction.
- Equality of lagging and leading output.
- Precise and continuous reactive power control with fast response.
- Possible active harmonic filter capability.

Structure Of 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.

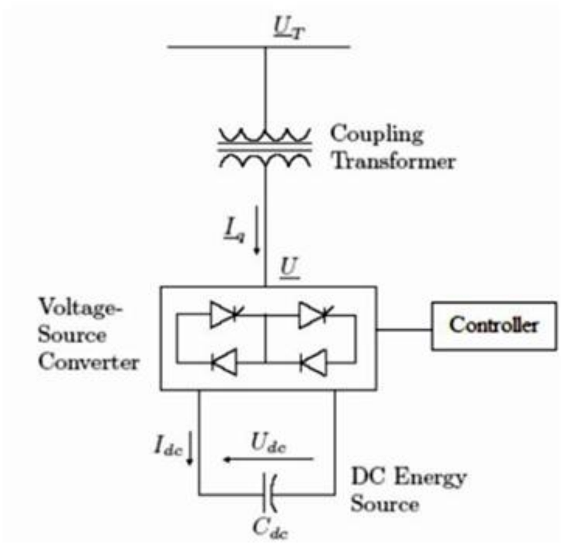

Fig. 2.4 Reactive power generation by a STATCOM

MODULE DESCRIPTION

A. UNIFIED POWER QUALITY CONDITIONER (UPQC)

A Unified Power Flow Controller (or UPFC) is an electrical device for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. It uses a pair of three-phase controllable bridges to produce current that is injected into a transmission line using a series transformer. The controller can control active and reactive power flows in a transmission line. The UPFC uses solid state devices, which provide functional flexibility, generally not attainable by conventional thyristor controlled systems. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a

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common DC voltage link. The main advantage of the UPFC is to control the active and reactive power flows in the transmission line. If there are any disturbances or faults in the source side, the UPFC will not work. The UPFC operates only under balanced sine wave source. The controllable parameters of the UPFC are reactance in the line, phase angle and voltage. The UPFC concept was described in 1995 by L. Gyugyi of Westinghouse. [1] The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system.

B. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

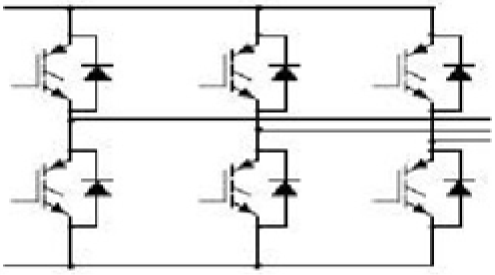
A static synchronous compensator (STATCOM), also known as a "static synchronous condenser" ("STATCON"), is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family of devices. It is inherently modular and electable. Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are however, other uses, the most common use is for voltage stability. A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source. For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; conversely, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power. The response time of a STATCOM is shorter than that of a static VAR compensator (SVC), mainly due to the fast switching times provided by the IGBTs of the voltage source converter. The STATCOM also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage (as the current can be maintained at the rated value even down to low AC voltage).

C. POWER QUALITY

Power quality determines the fitness of electric power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power. The electric power industry comprises electricity generation (AC power), electric power transmission and ultimately electric power distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised. While "power quality" is a convenient term for many, it is the quality of the voltage—rather than power or electric current—that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable.

D. SERIES INVERTER AND SHUNT INVERTER

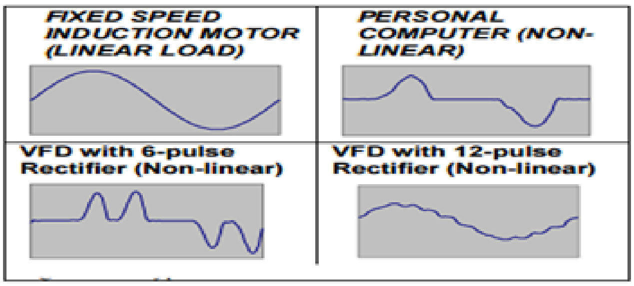
The circuit is basically an extension of the H-bridge-style single-phase inverter, by an additional leg. The control strategy is similar to the control of the single-phase inverter, except that the reference signals for the different legs have a phase shift of 120° instead of 180° for the single-phase inverter. Due to this phase shift, the odd triple harmonics (3rd, 9th, 15th, etc.). To compensate for this voltage reduction, the fact of the harmonics cancellation is sometimes used to boost the amplitudes of the output voltages by intentionally injecting a third harmonic component into the reference waveform of each phase leg.



Fg.4.Series and shunt Inverter

E.NON-LINEAR LOAD:

A load is considered non-linear if its impedance changes with the applied voltage. The changing impedance means that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.



Fg.5.Non-linear load

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 (LS), a resistor (RrmSag), and a breaker (SSag). To cause a voltage sag at bus A, SSag is closed.

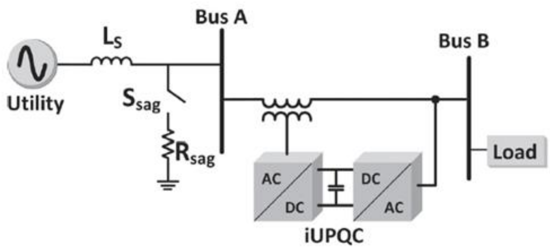


Fig. 6.1 iUPQC experimental scheme

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 SSag is closed to cause the voltage sag. To verify the grid-voltage regulation, the control of the QSTATCOM variable is enabled to compose (4) at instant t = 0 s. In this experimental case, LS = 10 mH, and RSag = 7.5 Ω. Before the QSTATCOM 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 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 SSag is permanently closed, with a LS = 10 mH and a RSag = 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. Even after the load connection, at t = 0 s, the voltages are still regulated,

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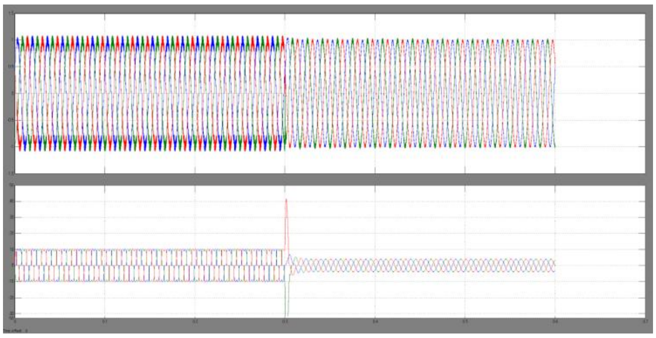
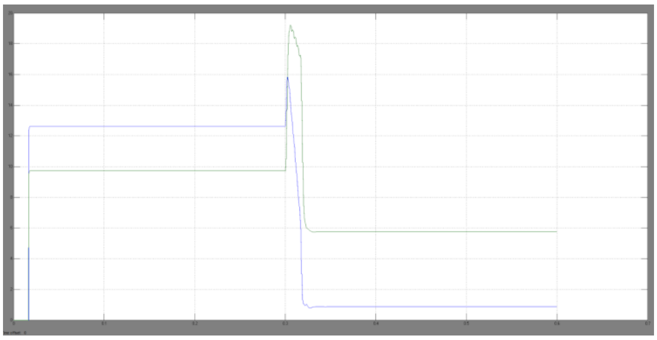
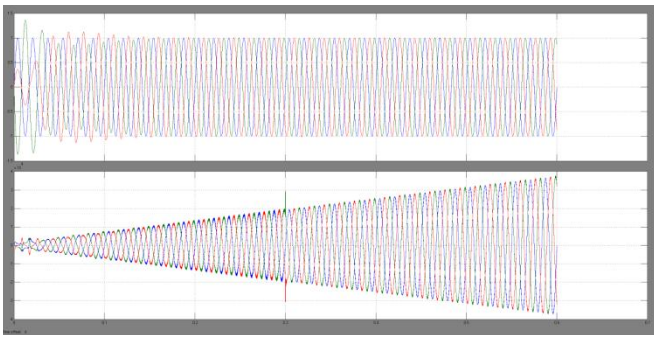
and the currents drawn from bus A are almost sinusoidal. Hence, the iUPQC can perform all the power-quality compensations, as mentioned before, including the grid-voltage regulation. It is important to highlight that the grid-voltage regulation is also achieved by means of the improved iUPQC controller.

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 RrmSag = 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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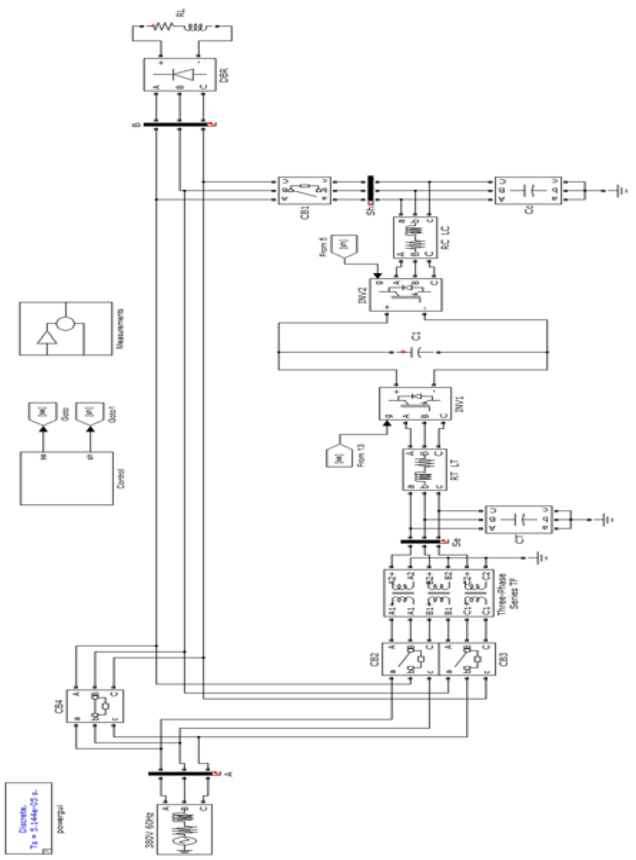

CONCLUSION

The paper illustrates the operation and control of an interline unified power quality conditioner (IUPQC). An effective PLL based control technique is used for IUPQC to detect and extract the PQ disturbances in power system. Each phase of Series and Shunt Compensator are investigated independently with PLL based controller. Custom power devices like DVR, DSTATCOM, and UPQC can enhance power quality in the distribution system. Based on the power quality problem at the load or at the distribution system, there is a choice to choose particular custom power device with specific compensation. Unified Power Quality Conditioner (UPQC) is the combination of series and shunts APF, which compensates supply voltage and load current imperfections in the distribution system. A simple control technique based on unit vector templates generation is proposed for UPQC. Proposed model has been simulated in MATLAB. The simulation results show that the input voltage harmonics and current harmonics caused by nonlinear load can be compensated effectively by the proposed control strategy. The closed loop control schemes of direct current control, for the proposed UPQC have been described.

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