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Dual Control Strategy Based Three-Phase Four-Wire Distribution Systems in Unified Power Quality Conditioner for Power Factor Improvement

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ABSTRACT— *This paper presents the study, analysis and practical implementation of a versatile unified power quality conditioner (UPQC), which can be connected in both three-phase three-wire or three-phase four-wire distribution systems for performing the series-parallel power-line conditioning. Thus, even when only a three-phase three-wire power system is available at a plant site, the UPQC is able to carry out power-line compensation for installed loads that require a neutral conductor to operate. Different from the control strategies used in the most of UPQC applications in which the controlled quantities are nonsinusoidal, this UPQC employs a dual compensation strategy, such that the controlled quantities are always sinusoidal. Thereby, the series converter is controlled to act as a sinusoidal current source, whereas the parallel converter operates as a sinusoidal voltage source. Thus, because the controlled quantities are sinusoidal, it is possible to reduce the complexity of the algorithms used to calculate the compensation references. Therefore, since the voltage and current controllers are implemented into the synchronous reference frame, their control references are continuous, decreasing the steady-state errors when traditional proportional-integral controllers are employed. Static and dynamic performances, as well as the effectiveness of the dual UPQC are evaluated by means of experimental results..*

Keywords: Power Quality (PQ), Unified Power Quality Conditioner (UPQC), Electrical power distribution systems (EPDS).

I. INTRODUCTION

Electrical power distribution systems (EPDS) with single-wire earth return (SWER) have been commonly adopted as a solution for electrical power supplying. This is due to the fact that the reduction of costs in the distribution of energy to serve large territorial extensions with low demographic densities is an important requirement, since lower installation and maintenance costs are achieved.Other alternatives are the use of energy distribution by means of two conductors (phase-toneutral) without earth return or even using two-phase systems (phase-to-phase). Considering these alternatives, capital investments for the realization of SWER distribution grid facilities installations are still lower.

Unified power quality conditioner (UPQC) is one of the progressed forms of power conditioning device, which is a combination of back to back connected series APF (SAPF) and shunt active power filter (PAPF) attached to a common DC link voltage. This topology will facilitates this equipment to have a reduced dc-link voltage without reducing its compensation capability. This device is principally used in getting better the power quality. The demand for power quality (PQ) improvement has been expanding in recent years, mainly because of the increase of nonlinear loads attached to the electrical power system causing distortions in the utility voltages at the point of common coupling[1]. Nowadays Power quality problems have received a great attention because of their impacts on both utilities and customers. Unified power quality conditioner is one of the best custom power device used to compensate both source and load side problems.

N rural or remote regions in Brazil, as well as in some areas of countries such as Australia and New Zealand, for instance, electrical power distribution systems (EPDS) with single-wire earth return (SWER) have been commonly adopted as a solution for electrical power supplying. This is due to the fact that the reduction of costs in the distribution of energy to serve large territorial extensions with low demographic densities is an important requirement [1] - [5], since lower installation and maintenance costs are achieved [4], [6].

Other alternatives are the use of energy distribution by means of two conductors (phase-toneutral) without earth return, or even using two-phase systems (phase-to-phase). Considering these alternatives, capital investments for the realization of SWER distribution grid facilities installations are still lower [7]. The demand for electrical energy in single-phase rural distribution grids has considerably increased in the last decades, both in agriculture and in livestock, mainly due to the increasing evolution and modernization of the technologies used, as well as the increase in the mechanization of production processes. It is possible to mention, for example, the automation of irrigation, as well as the post-harvest agricultural processing involving seed selection and milling, ventilation and refrigeration, washing and packaging lines, among others. Within this context, there is an imminent trend of increasing energy demand in rural properties, as well as the need to improve power quality enhancement due to the change in the characteristics of the loads. The voltage regulation is characterized as one of the main problems of power quality (PQ) found in the rural singlephase grids [4], [5], because when subjected to large loads, these grids have significant voltage drops, whereas at times of low consumption the voltage tends to rise [1]. Nevertheless, a solution not so efficient due to constant load variations can be adopted by adjusting the taps of the transformer of the SWER network. Another solution, more efficient in this case, is the use of single-phase voltage regulators [5]. Some ways to bypass large capital investments to meet the growing demand of rural properties have been adopted [3], [8]. In [3] the impacts caused between distributed generation systems implemented through photovoltaic systems and the SWER distribution systems are presented. On the other hand, in [8], the use of energy storage systems by means of batteries and their use at peak demand is discussed. It is possible to notice an increasing need to use three-phase distribution grids to meet the demand for electrical energy in rural areas due to changes in the characteristics of the loads. Currently, most of them could be driven by three-phase induction motors instead of single-phase motors, for they have a higher starting torque [7]. Furthermore, the use of medium and high power three-phase voltage inverters involved in modern automated systems also justifies the need for threephase grids in rural areas. Therefore, the presence of a local three-phase energy distribution system in areas that make use of the SWER distribution system becomes more and more indispensable. For this purpose, several solutions and/or configurations of single-phase-to-three-phase (1Ph-to-3Ph) converters have been addressed in the literature [6], [7], [9]-[11]. These include 1ph-to-3Ph four-wire converters, which are able of supplying three-phase and single-phase loads [6], [7], [9], or 1Ph-to-3Ph three-wire converters intended to supply only three-phase loads [10], [11]. Dedicated to feed three-phase three-wire loads and integrating the functioning of the unified power quality conditioner (UPQC), the 1Ph-to-3Ph converter presented in [12] performs universal filtering, i.e., it operates as seriesparallel active power filter, in which the series converter is composed of a single-phase full-bridge inverter (two inverter legs), while the parallel converter is composed of a threephase three-leg inverter, totaling five inverter legs. In [13], also integrating the functionality of a UPQC, a 1Phto-3Ph converter was dedicated for creating a local threephase four-wire (3P4W) EPDS from a single-phase distribution system. The series converter is composed of a half-bridge inverter (one inverter leg), while the parallel converter is composed of a three-leg split-capacitor inverter, totaling four inverter legs. Thus, it was allowed feed singleand three-phase loads. On the other hand, limited results have only been presented by means of simulations. In addition, no detail regarding to the dimensioning and control of the converters were suitably treated.

It is also observed that the performances of the controllers are notably better when they operate with sinusoidal references, when compared to those that use non-sinusoidal references. In addition, since the control references are sinusoidal, the controllers implemented in the synchronous reference frame will have continuous reference of voltage and current, facilitating even more the control [19]. Another advantage of dual compensation is in the form of generation of control references, which is performed only with the use of a Phase-Locked Loop (PLL) system [20]. The main contribution presented in this paper is to validate experimentally the UPQC-1Ph-to-3Ph destined to feed singleand three-phase loads from the SWER power distribution systems, commonly found in rural and/or remote areas and suffer with PQ problems. By adopting the dual compensation strategy, the proposed UPQC-1Ph-to-3Ph makes possible to drain from the single-phase electrical grid a sinusoidal current in phase with the grid voltage. Furthermore, the system can also suppress harmonics from the grid voltage, as well as compensate for voltage disturbances, such as voltage sags/swell. In other words, the UPQC-1Ph-to-3Ph can conceive a local 3P4W system with regulated, balanced and sinusoidal load voltages with low harmonic contents improving the PQ indicators [23]. Therefore, the proposed system can achieve two important functions simultaneously, as described: i. convert the single-phase grid into a three-phase grid, generating a 3P4W distribution system with earthed neutral wire to the final consumer, allowing to connect singleand there-phase loads; ii. perform the series and parallel active power filtering improving PQ indicators, such as power factor, harmonic distortion [23]. Furthermore, in order to assist in the proper dimensioning of the UPQC-1Ph-to-3Ph power converters, an analysis involving the power flow through the serial and parallel converters is also presented.

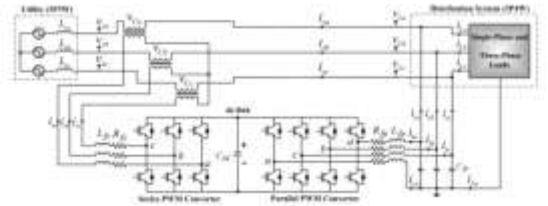


Fig1: 3P4W distribution system based on UPQC topology connected to 3P3W power system.

II. PROBLEM DEFINITION

For this purpose, several solutions and/or configurations of single-phase-to-three-phase (1Ph-to-3Ph) converters have been addressed in the literature [6], [7], [9]-[11]. These include 1ph-to-3Ph four-wire converters, which are able of supplying three-phase and single-phase loads [6], [7], [9], or 1Ph-to-3Ph three-wire converters intended to supply only three-phase loads [10], [11]. Dedicated to feed three-phase three-wire loads and integrating the functioning of the unified power quality conditioner (UPQC), the 1Ph-to-3Ph converter presented in [12] performs universal filtering, i.e., it operates as seriesparallel active power filter, in which the series converter is composed of a single-phase full-bridge inverter (two inverter legs), while the parallel converter is composed of a threephase three-leg inverter, totaling five inverter legs. In [13], also integrating the functionality of a UPQC, a 1Phto-3Ph converter was dedicated for creating a local threephase four-wire (3P4W) EPDS from a single-phase distribution system. The series converter is composed of a half-bridge inverter (one inverter leg), while the parallel converter is composed of a three-leg split-capacitor inverter, totaling four inverter legs. Thus, it was allowed feed singleand three-phase loads. On the other hand, limited results have only been presented by means of simulations. In addition, no detail regarding to the dimensioning and control of the converters were suitably treated. In this paper, the 1Ph-to-3Ph converter presented in [13] is experimentally validated. It is called UPQC-1Ph-to-3Ph and its power circuit configuration is shown in Fig. 1. This system is indicated for applications in rural or remote areas where, for economic reasons, only single-phase EPDS, such as SWER system, is accessible to the consumer. Once the proposed system deployed in this paper was conceived based on the UPQC functionalities, some discussions related to the UPQC should be performed. Since they simultaneously perform the functions of series active power filter (SAPF) and parallel active power filter (PAPF), the UPQCs have been commonly employed to mitigate PQ problems, both in single-phase distribution systems [14] and in 3P4W distribution systems [15]-[19]. Usually, the UPQCs are controlled to perform series and parallel compensation, synthesizing non-sinusoidal quantities of voltage and current, i.e., the series converter synthesizes non-sinusoidal voltage quantities to compensate for grid voltage disturbances, while the parallel converter synthesizes non-sinusoidal current quantities with the purpose of suppressing harmonic currents and compensating the reactive power of the loads [15]. For this compensation strategy, some calculation method capable of generating the voltage and current compensation references should be used. On the other hand, some studies presented in the literature have used the dual compensation strategy to control the series and parallel converters of the UPQC [16]-[19]. In this strategy, sinusoidal voltage and current references are employed to control both the converters. In this case, the series converter synthesizes sinusoidal current quantities and, consequently, operates as a sinusoidal current source, providing a high impedance path for the current harmonics of the load. The parallel converter synthesizes sinusoidal voltage quantities and, in this case, operates as a sinusoidal voltage source, providing a low impedance path for the current harmonics of the load.

III. CONTROL REFERENCES OF SERIES & PARALLEL CONVERTERS

A. Current Reference of the Series Converter:

The single-phase current reference used to control the SAPF is obtained in the synchronous reference frame dq, as shown in Fig. 2. Thus, the load currents (La i , Lb i , Lc i) are measured and transformed from the three-phase stationary reference frame (abc-axes) to the two-phase stationary reference frame ( ) using the Clarke transformation. Then, by–0 axes βα means of the Park transformation, the stationary current quantities of the reference frame 0βα are transformed to the synchronous reference frame (dq-axes). In the rotating frame, the coordinates of the unit vector sin(θ) and cos(θ) are obtained using the PLL system presented in [20], in which θ is the estimated phase-angle of the grid voltage. The quantity d i , shown in Fig. 2, represents the active components of the load currents, i.e., it is composed of an average component and oscillating components in the reference frame d (d-axis).

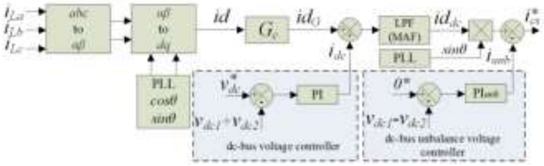


Fig2: Generation scheme of the series converter current reference the synchronous reference frame dq

B. Voltage Controller of the Parallel Converter

Fig. presents, by means of a block diagram, the voltage control loops as well as the average model of the parallel converter considering only phase "a". The multi-loop control is implemented by an internal current control loop, where only a proportional controller is used, and an external voltage control loop, in which a PI controller is used. Thus, from the diagram of Fig. 4, the transfer function of the system.

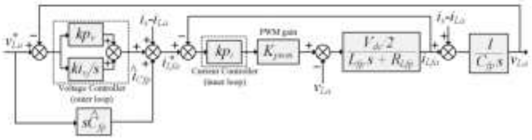


Fig3: Block diagram of the voltage control loops and of the average model of the parallel converter

C. DC-Bus Voltage Controller

By adopting a procedure similar to that presented in [22], it is possible to obtain the voltage control of the dc-bus diagram as shown in Fig. 6. Thus, the small signal closed-loop transfer function of the dc-bus control system

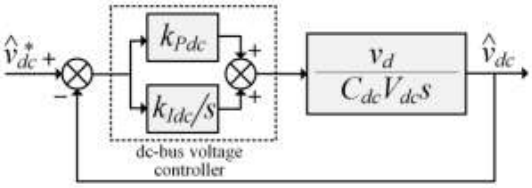


Fig4: Block diagram of the dc-bus control system.

1V. FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

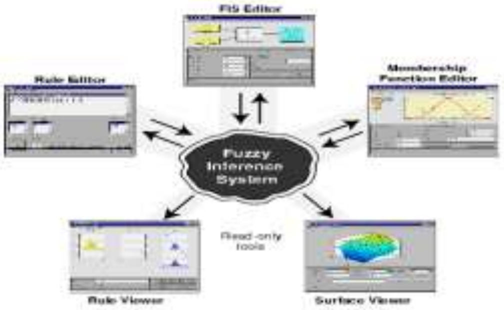


Fig. 5 The Primary GUI Tools Of The Fuzzy Logic Toolbox

The FIS Editor handles the high level issues for the system: How much input and output variables? What are their names? The Fuzzy Logic Toolbox doesn't limit the number of inputs. However, the number of inputs may be limited by the available memory of your machine. If the number of inputs is too large, or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other GUI tools.

The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behavior of the system.

THE FIS EDITOR:

The following discussion walks you through building a new fuzzy inference system from scratch. If you want to save time and follow along quickly, you can load the already built system by typing fuzzy tipper This will load the FIS associated with the file tipper.fis (the .fis is implied) and launch the FIS Editor. However, if you load the pre-built system, you will not be building rules and constructing membership functions.

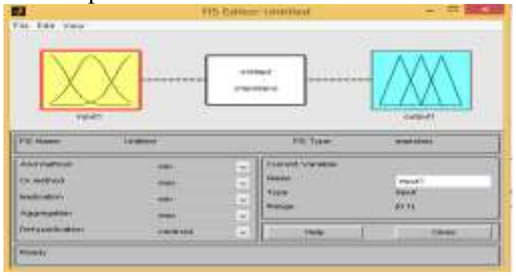
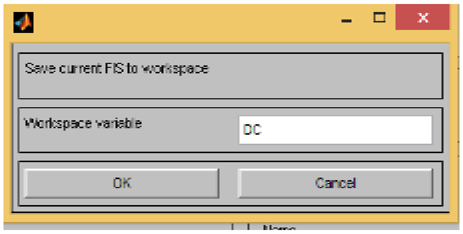


Fig6. The FIS Editor

You will see the diagram updated to reflect the new names of the input and output variables. There is now a new variable in the workspace called tipper that contains all the information about this system.



Save current FIS to workspace

Workspace variable: DC

Fig7. **'Save** to workspace as...' window

By saving to the workspace with a new name, you also rename the entire system. Your window will look like as shown in Fig.

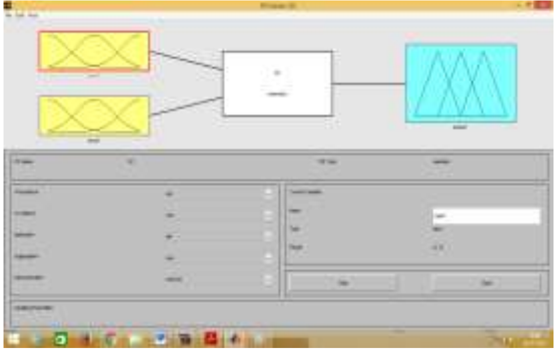


Fig8.The Updated FIS Editor

THE MEMBERSHIP FUNCTION EDITOR:

Fig9.The Membership Function Editor

FIG10: The Updated Membership Function Editor

THE RULE EDITOR:

Fig.11 The Rule Editor

	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Fig12: Fuzzy rules

V. SIMULINK MODEL

The Simulink developed by Math Works, is a data flow graphical programming language tool for modeling, simulating and analyzing multi domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi domain simulation and Model-Based Design. From the MATLAB model it was possible to build and test UPQC systems and to optimize their performance before implementation on the actual equipment. This allowed faster development and the opportunity to investigate control. For the purpose of controller design, model verification and evaluation were modeled in MATLAB using SIMULINK. Fig 2 shows the MATLAB Simulation of Dual unified power quality conditioner. Having series and shunt active power filters with IGBTs.

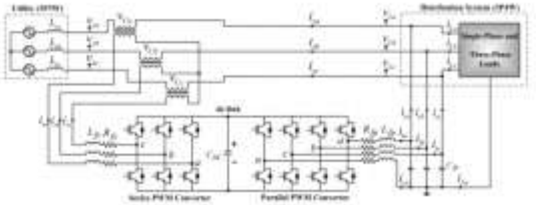


Fig. 13: Simulation of Dual UPQC

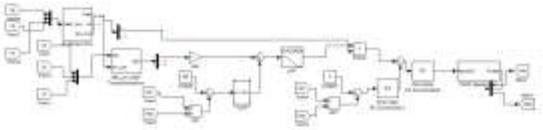


Fig. 14: Series PWM inverter

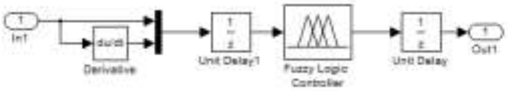


Fig15: Fuzzy logic controller

5.1SIMULATION RESULTS:

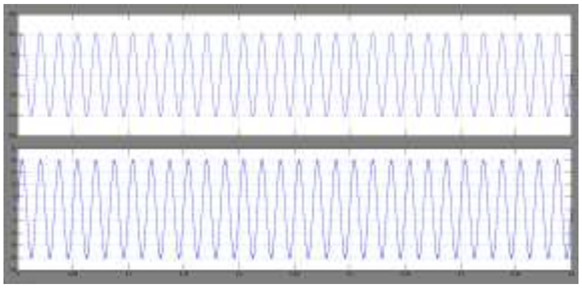


Fig16: Source Voltage and current

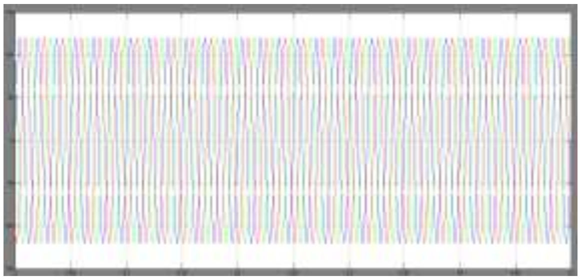


Fig17: Inverter inductor 3-phase voltages

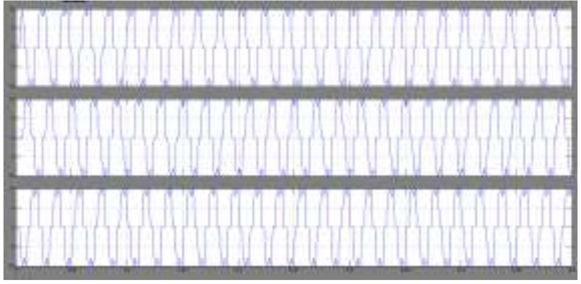


Fig18: Inverter inductor 3-phase Currents

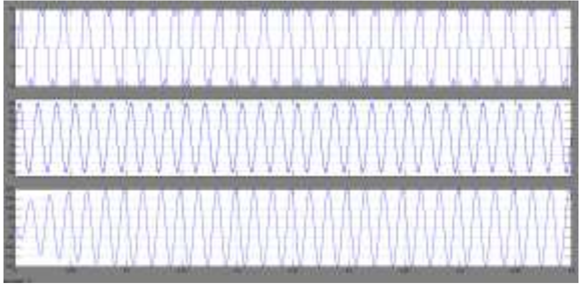


Fig19: (a): Inverter current, (b): Source current (c): parallel converter cpa

VI. CONCLUSION

This paper presents a practical and versatile application based on UPQC, which can be used in three-phase three-wire (3P3W), as well as three-phase four-wire (3P4W) distribution systems. It was demonstrated that the UPQC installed at a 3P3W system plant site was able to perform universal active filtering even when the installed loads required a neutral conductor for connecting one or more single-phase loads (3P4W). The series-parallel active filtering allowed balanced and sinusoidal input currents, as well as balanced, sinusoidal and regulated output voltages. By using a dual control compensating strategy, the controlled voltage and current quantities are always sinusoidal. Therefore, it is possible to reduce the complexity of the algorithms used to calculate the compensation references. Furthermore, since voltage and current SRF-based controllers are employed, the control references become continuous, reducing the steady-state errors when conventional PI controllers are used. Based on digital signal processing and by means of extensive experimental tests, static and dynamic performances, as well as the effectiveness of the dual UPQC were evaluated, validating the theoretical development.

FUTURE SCOPE:

The Fuzzy based Sliding Mode Control based System enhances the stability of the system and improves the dynamic response of the system operating in faulty conditions in a better way and it has also effectively enhanced the damping of electromechanical oscillations according to non-linear simulation results.

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