Reactive Power Flow Control of a Dual Unified Power Quality Conditioner

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***Abstract*—This paper presents a way to balance the reactive power processed between series and parallel active filters that compose the Dual Unified Power Quality Conditioner (iUPQC) through the power angle control (PAC). The proposed new methodology divides equally the reactive power between the filters according of load demand. It will be presented a review of the iUPQC operation, the concept of power angle control, the mathematical deduction of the power angle control used for reactive power equalization, the analysis of power flow between iUPQC filters and simulations to validate the proposed control.**

Keywords— unified power quality conditioner (UPQC), power angle control (PAC), power quality, reactive power compensation.

I. INTRODUCTION

The Unified Power Quality Conditioner (UPQC) is a device used to improve the power quality, formed by the junction of the active filters series and parallel. This power conditioner is able to compensate the harmonic components from non-linear loads, making the input Power Factor (PF) close to the unit, and balance the load currents drained of the grid. The load voltages are balanced and grid disturbances like sags and swells are eliminated. The harmonic components of the grid voltages are compensated too, providing a balanced sinusoidal voltage to the load [1].

In standard operation of this type of power conditioner, the series active filter – SrAF, is voltage controlled and is responsible for eliminate voltage disturbances from the grid. The shunt active filter – ShAF, is current controlled and is responsible for eliminate the harmonic content of the load current [1].

Among many UPQC topologies [1], we can found the iUPQC [2]. In this topology the ShAF is voltage controlled and is responsible to provide a sinusoidal voltage to the load, regulated, balanced and free of harmonics. The input grid current imposed by the current controlled SrAF, which ensure unitary power factor and balanced grid currents. Fig. 1 shows the iUPQC system, presenting the main waveforms of the circuit [3].

As the current through the SrAF is sinusoidal and in phase with the grid voltage V_S, the load current harmonics and reactive components in the fundamental frequency are forced to circulate through the ShAF, because it is a low impedance path for non-active load currents. Any voltage disturbance on the grid like sags, swells, short interruptions, unbalances and harmonics, will not reach the load because ShAF impose a sinusoidal voltage to the load.

Thus, it can be said that, indirectly, the voltage present at the SrAF compensates the load voltage, because that voltage is the difference between the load voltage and the source voltage. Similarly, the current processed by the ShAF, indirectly, compensate the grid current, since the current in the ShAF is the difference between the load current and the grid current.

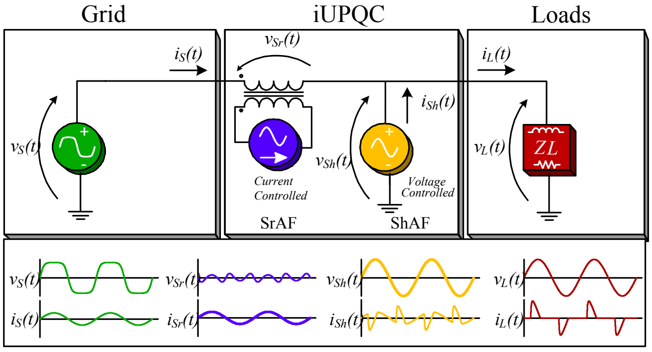

Fig.1 – Dual Unified Power Quality Conditioner (iUPQC) and its main waveforms.

Some works about UPQCs proposed to use a displacement between the grid voltage and the load voltage aiming to change a power flow between the SrAF and ShAF. [1] This technique is called as Power Angle Control (PAC).

Among this works, a method proposed by [4] aims at minimizing the amount of active power injected by a UPQC-Q, which minimizes sags using reactive power. The proposal of [5] aims to reduce the apparent power processed by UPQC decreasing the DC bus voltage, [6] aims to minimize losses in the semiconductor switches, since [7] propose the converter loss reduction in an iUPQC. Finally, [8] proposes simultaneous compensations of voltage Sag/Swell and load reactive power using the SrAF.

Another work using the PAC was proposed by Khadkikar and Chandra [9], which divides the reactive power between the SrAF and ShAF of a UPQC.

Finally, this work aims to implement a iUPQC control strategy, adapted from [9], in order to balance the reactive power processed by the active filters that compose this equipment and thus allow modularization of the active filters, optimizing its design and manufacture.

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II. Power Flow on UPQC and iUPQC

Despite the ShAF be controlled by voltage and the SrAF by current, the iUPQC has the same power flow behavior than the conventional UPQC, as shown below.

A. iUPQC Blocs Diagram

Both ShAF as ShAF are composed by drivers and passive filters to reduce the effects caused by high frequency switching. The main differences between these filters are the control implemented in each and SrAF uses a coupling transformer for the connection to the grid, while ShAF is connected directly between the source and the load.

The junction of these two active filters, by sharing a DC bus, form the standard iUPQC as can be seen in Fig. 2.

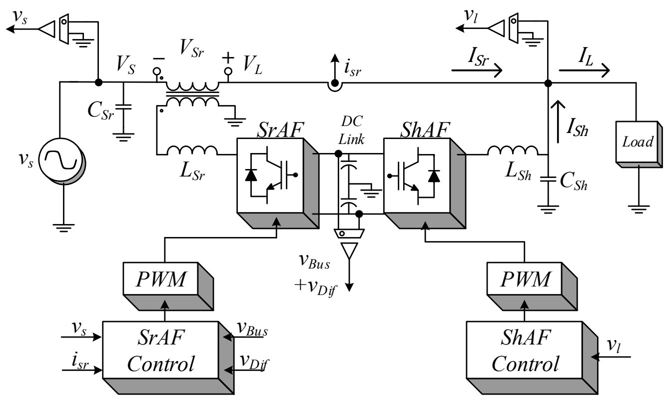

Fig.2 – iUPQC power structure and control representation.

The SrAF share the DC bus with the ShAF, forming a back-to-back structure, and, in certain situations, both filters process power, one absorbing and the other returning power to the grid. Unlike conventional UPQC, the active filters location in iUPQC is fixed, and the SrAF located between the power supply and load, and ShAF is connected between the SrAF and the load.

B. Power Flow analysis

Considering the iUPQC in an ideal situation, i.e., without loss of its components, network without imbalance, linear and balanced load, network and load without harmonics, the active power flow occurs simultaneously in both filters only when there is a RMS voltage difference between the source voltage, V_S, and the load voltage V_L [3]. When V_S is less than V_L, the ShAF drains active power while the SrAF provides active power and when V_S is greater than V_L the SrAF drains active energy and ShAF provides active power to the system, in this way:

$$P_S = P_{Sr} + P_{Sh} + P_L \tag{1}$$

Considering iUPQC with no losses,

$$P_S = P_L \tag{2}$$

$$P_{Sr} = -P_{Sh} \tag{3}$$

SrAF controls the grid current, I_s , to aim a PF close to unity, thus V_S and I_S will be in phase, consequently the angle between V_S and I_S, φ_S, will be zero. So, considering both sinusoidal, there will be no reactive power flow through the SrAF. Analyzing the reactive power system, according to (4), the ShAF compensate the reactive power load Q_L (5).

$$Q_S = Q_{Sr} + Q_{Sh} + Q_L \tag{4}$$

$$Q_L = -Q_{Sh} \tag{5}$$

Given the analysis of equations (1) - (5), the entire reactive power drawn by the load must be compensated by ShAF, thus the power flow necessary for this correction flows through this filter, as occur in the conventional UPQC.

III. Power Angle Control

If the controlled load voltage is not in phase with the grid current, this it would generate an angle difference between the grid voltage and load voltage, but this may occur without altering the magnitude of the resultant load voltage, so a certain amount power, reactive and active, would flow through filter series. Using the proper control of the angle between the grid and the load voltage, i.e., the PAC, the SrAF can also help in load power compensation, without consuming additional active power from the grid, under normal operating conditions, i.e., with no losses and linear load.

The phasor representation of PAC operation is in Fig. 3. Assuming an ideal system which V_S e V_L have the same amplitude, balanced voltages without loss and other disturbances. The ShAF should impose a new voltage V'_L at the load, with the same voltage amplitude of the grid voltage and angle δ. This causes an advance in the current phasor I_L to I'_L keeping the original angle between grid voltage and current φ_L. So the effective angle between the load current and source voltage changes from φ_L to β, resulting in a reduction of the reactive power handled by the ShAF. In other words, by changing the δ, the angle between the grid voltage and the load voltage, the SrAF also processes reactive power. The amount of power processed by the SrAF is what defines $\delta_{máx}$, which can be found without overloading the SrAF. This power division method results in a better utilization of SrAF and reduces the load on the ShAF.

IV. Computing Mathematics

In order to implement the PAC is necessary to estimate δ based on the load reactive demand and instantaneously. According to [9] we should establish a $\delta_{máx}$ in order to not compromise the SrAF capacity through an overloading. In this work, the reactive power will be automatically shared between the SrAF and ShAF, regardless of the power consumed by the load.

A. SrAF parameters

The first step is to set up the iUPQC parameters, the voltage amplitude across the SrAF, V_{Sr}, and its angle related of grid voltage. Figure 4 shows the detailed phasor diagram used to calculate the voltage injected in series, where k is the nominal RMS value of the load voltage.

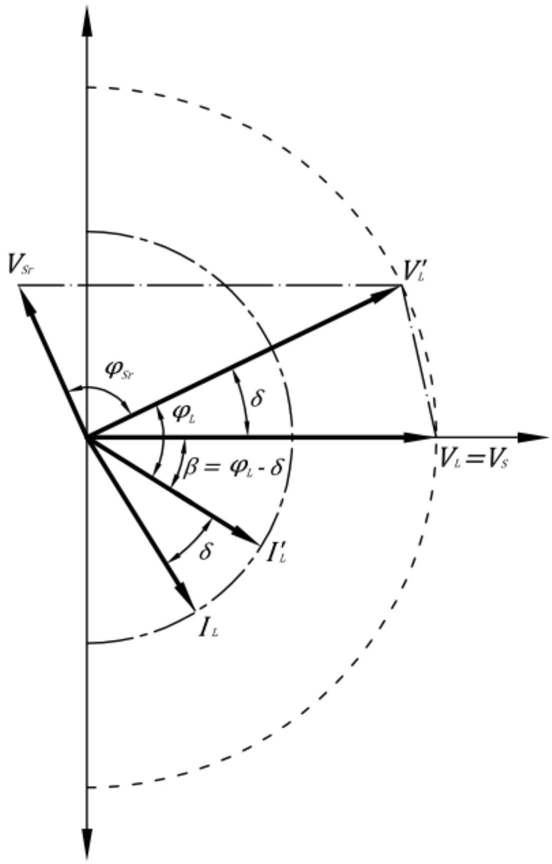

Fig.3 – PAC Phasor Diagram.

The mathematical derivations are explained in [9], where was obtained the equation that represents the voltage vector in the SrAF with phase and module and only in function of δ, as shown in (6) e (7).

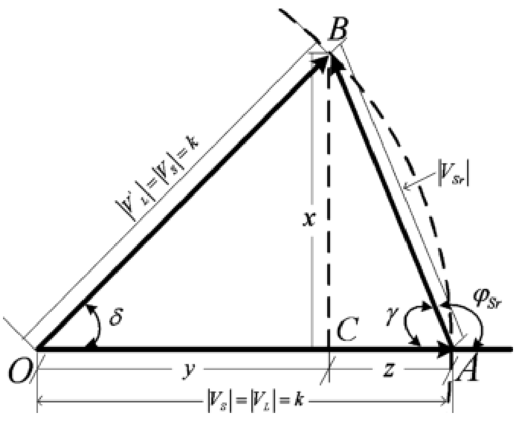

Fig.4 – V_{sr} and φ_{sr} phasors.

$$|V_{sr}| = k\sqrt{2}\sqrt{1-cos(\delta)} \tag{6}$$

$$\varphi_{sr} = 180° - \gamma \tag{7}$$

B. ShAF parameters

The Fig. 5 shows the phasor diagram for different currents generated due to the insertion of δ. Without the PAC, the reactive load was completely processed by ShAF, by injecting compensation current I_{Sh}. With PAC, the phasor load current becomes I'_L and it is created a new ShAF current, I'_{Sh}, with an angle displacement and a lower amplitude compared to the previous current I_L. The grid current I_S isn't change, because the SrAF ensure the high power factor. After the phase shift, a new active component appears in the ShAF current.

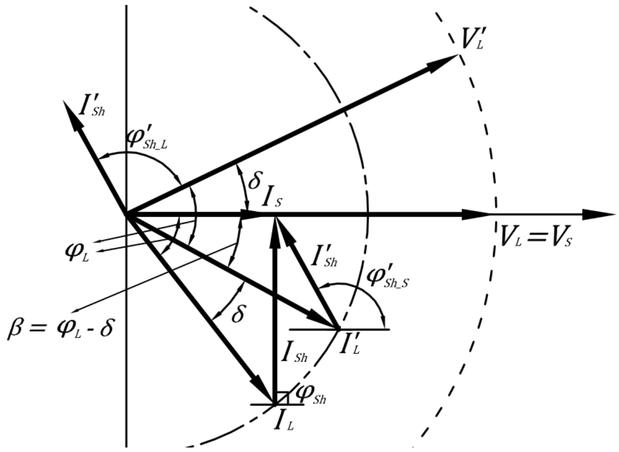

Fig.5 – Phasor diagrams of currents after the PAC.

The Fig. 6 shows in detail the compensating phasor of current I'_{Sh} and its angle φ'_{Sh_S}, between the current and the grid voltage.

Equations (8) and (9) give the amplitude and angle of the current injected by ShAF, I'_{Sh}, in function of δ. The detailed knowledge of these equations can be seen in [9].

$$|I'_{Sh}| = |I_L|\sqrt{1+cos^2(\varphi_L)-2cos(\beta)cos(\varphi_L)} \tag{8}$$

$$\varphi'_{ShL} = \alpha + 90° - \delta \tag{9}$$

The equations (6) through (9) shows the resulting changes, caused by PAC in the load voltage and ShAF current. The effectiveness of this method depends entirely on generating a signal based on these values in real time. For a regular load condition, the parameters I_L e φ_L can be considered constant or without abrupt changes, so the PAC is independent of other system parameters, resulting in a robust and effective approach to power compensation for both iUPQC filters.

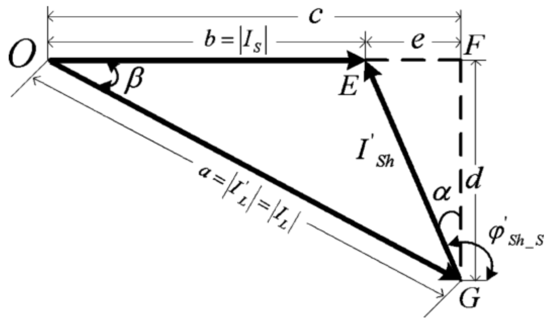

Fig.6 – I'_{Sh} e φ'_{Sh_S} phasors.

(10)

C. Boundary condition for $\delta_{máx}$

Usually the SrAF dimensioning depends on the sags percentage that this filter will compensate [9]. If the maximum voltage that the series filter may add to the circuit is called $V_{Sr,\,max}$ and the percentage of the limit in terms of the desired voltage is called factor k_{Sr}, then $\delta_{máx}$ can be define.

$$S_{FAS} = V_{Srmax} I_S^*$$

From equation (6), $\left|V_{Srmax}\right| = k\sqrt{2}\sqrt{1-cos\left(\delta_{max}\right)}$ (11)

$$k_{Sr}k = k\sqrt{2}\sqrt{1-cos\left(\delta_{max}\right)} \tag{12}$$

$$k_{Sr} = \sqrt{2}\sqrt{1-cos\left(\delta_{max}\right)} \tag{13}$$

$$\delta_{max} = \cos^{-1}\left(1-\frac{k_{Sr}{}^2}{2}\right) \tag{14}$$

In a usual application of iUPQC the power of both filters would be known. Using (14), its possible to calculate the maximum angle $\delta_{máx}$ which can be used without overloading the SrAF already installed. Thus, the limit of $\delta_{máx}$ will ensure that the reactive power is divided between the filters without overloading neither.

D. Resolve δ

The method proposed in [9] proposes that SrAF only process power after a power threshold set for the ShAF be exceeded, otherwise the ShAF assume all reactive power.

Being $Q_{L,max}$ the maximum reactive demand that the iUPQC supports, this load will be divided between the active filters. Thus it defines that the maximum demand that ShAF and SrAF will process as $Q_{L,max}/2$. The reactive power that the SrAF will process is defined as:

$$Q_{Sr} = kI_S\sin\left(\delta\right) \tag{15}$$

Rewriting (15), considering P_S=P_L, because there is no active power consumption between the filters, it is possible to equate δ only in function of the SrAF reactive power and the load active power.

$$\sin\left(\delta\right) = \frac{Q_{Sr}}{kI_S} \tag{16}$$

$$\sin\left(\delta\right) = \frac{Q_{Sr}}{P_S} \tag{17}$$

$$\delta = \sin^{-1}\left(\frac{Q_{Sr}}{P_S}\right) = \sin^{-1}\left(\frac{Q_{Sr}}{P_L}\right) \tag{18}$$

In order to modularize the iUPQC, it is necessary that the reactive power is divided equally between the filters in any situation. Thus, changing the reference of reactive energy in equation (18) by the half of Q_L, we have the new δ value:

$$\delta = \sin^{-1}\left(\frac{0{,}5Q_L}{P_L}\right) \tag{19}$$

Therefore, the reference will always be a half of the load reactive power, and it will ensure the power balance between the filters only in function of load and with no pre-established fixed value. The Fig.7 shows a block diagram of how this new angle is obtained through measurements of instantaneous load power (P_L and Q_L) and this angle must be added to the sinusoidal reference of the load voltage controlled by the ShAF.

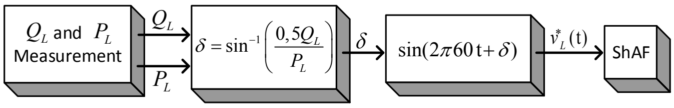

Fig.7 – Flowchart for the PAC implementation

E. Active and reactive power flow with PAC

This section provides an analysis of single-phase active and reactive power flow flowing between iUPQC filters.

The equations (20) and (21) show the SrAF powers without the PAC:

$$P_{Sr} = V_{Sr}I_S\cos\left(\varphi_{Sr}\right) \tag{20}$$

$$Q_{Sr} = V_{Sr}I_S\sin\left(\varphi_{Sr}\right) \tag{21}$$

The equations (22) and (23) show the ShAF powers in the same condition:

$$P_{Sh} = V_L I_{Sh}\cos\left(\varphi_{Sh}\right) = kI_{Sh}\cos\left(\varphi_{Sh}\right) \tag{22}$$

$$Q_{Sh} = V_L I_{Sh}\sin\left(\varphi_{Sh}\right) = kI_{Sh}\sin\left(\varphi_{Sh}\right) \tag{23}$$

As comment earlier in an ideal system with a linear load, the SrAF don't process active or reactive power, and the shunt filter processes only the load reactive power.

With the PAC, a reactive and active power will flow through the SrAF. Using (6) e (20) and, after some algebraic operations [9], we have:

$$P_{Sr} = -kI_S\left(1-\cos\left(\delta\right)\right) \tag{24}$$

The negative sign in (24) indicates that during the operation with the PAC, the SrAF absorbs certain amount of active power, while the ShAF provide the same amount of active power to the AC point of common coupling (PCC). Thus the DC bus shared by the filters must receive current, and consequently active power, from the SrAF and deliver to ShAF to compensate this change in the converter operation.

The reactive power processed by the SrAF was shown in the equation (15), and its related with the angle δ. The reactive power processed by SrAF is directly proportional with the angle δ , as well as the SrAF voltage , according to equation (6) .

The active and reactive powers in the ShAF under PAC can be calculate using equations (25) and (26):

$$P'_{Sh} = V'_L\,I'_{Sh}\cos\left(\varphi'_{ShL}\right) = kI'_{Sh}\cos\left(\varphi'_{ShL}\right) \tag{25}$$

$$Q'_{Sh} = V'_L\,I'_{Sh}\sin\left(\varphi_{ShL}\right) = kI'_{Sh}\sin\left(\varphi'_{ShL}\right) \tag{26}$$

Thus the load reactive power can be defined by:

$$Q_L = Q'_{Sr} + Q'_{Sh} \tag{27}$$

V. NUMERIC SIMULATION

Was implemented a simulation using a single-phase system composed by a source, the iUPQC and loads. The circuit implemented can be seen in Fig. 8. The nominal iUPQC values used are shown in Table I and the software used was the PSIM. The simulation focus was to analyze the system behavior for a load with wide range of power and PF, so the load was composed by three RL impedances, each one consuming different values of power and PF. The loads were connected to the circuit in three different periods. The simulation starts with nominal power, S_N, and PF of 0.92. At 0.5 sec the load was decreased to a half of nominal power and PF was changed to 0.85. Finally the system was submitted to an overload of 30% with PF of 0.90. The iUPQC active filters were sized to support 833VA each.

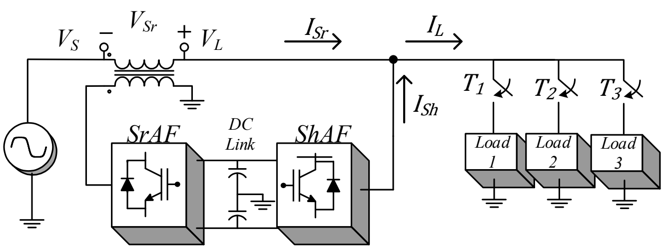

Fig.8 – System used for the simulation. The switches T1, T2 and T3 were connected in sequence, only one connected at a time.

Fig. 9 shows, along the three periods of simulation, the load active and reactive power, the angle δ, and reactive and aparent powers in SrAF and ShAF.

Note that according to the variation of P_L e Q_L, the angle δ also varies, and, hence, also vary the reactive powers on the filters. After the load changings, the reactive power values in each filter are very close to half of the reactive load Q_L. The exact values of the measures in steady state are in Table II.

TABLE I.

iUPQCs Simulated Values	
Nominal iUPQC Power (S_N)	833VA
Grid Voltage (V_S)	127V
Bus Voltage (V_{Bus})	400V
Switching frequency (f_s)	20kHz
Bus Capacitor (C_{Bus})	3mF
High Frequency Filter Inductors (L_{Sr}) e (L_{Sh})	650µH
Leakage inductance of transformer	2,98mH
ShAF HF Filter Capacitor (C_{Sh})	10µF
SrAF HF Filter Capacitor (C_{Sr})	1uF

TABLE II.

Measures	Values obtained from the simulation		
	T_1	T_2	T_3
$Q_L / 2$	160Var	108Var	230Var
Q_{Sr}	161Var	110Var	230Var
Q_{Sh}	160Var	102Var	234Var
Deviation	0.6%	5.5%	1.7%
δ	11.7°	17.5°	13.4°

In the first and third periods (T_1 and T_3), Q_{Sr} e Q_{Sh} are very close to $1/2\,Q_L$, with a maximum deviation of 1,7%. In the second period (T_2), Q_{Sr} has an deviation of 1.8% and Q_{Sh}, 5.5%. As expected, the apparent power in both filters is related with the reactive power, because in this setup both converters processed the same active and reactive powers. These measurement errors occur due to two causes. The first is due to the non-ideal behavior of control systems and modulations of the iUPQC active filters. The second cause is because the PCA was implemented in open loop.

VI. CONCLUSION

The purpose of this work was the equal division of reactive power processed between the iUPQC active filters. This was possible due a new proposed method to obtain the load angle between load voltage and grid voltage, also known as Power Angle Control (PAC).

It was shown that the iUPQC power flow is equal to the conventional UPQC power flow. The PAC concept was introduced and adapted to work with an iUPQC sharing the load reactive power between its filters.

Through simulations, it was verified that this method of phase angle control works property with load variations, dividing equally the reactive power between the filters.

The equal division of the processed powers enables better scaling of the iUPQC active filters, making it possible the modularization and facilitating its manufacturing by industry.

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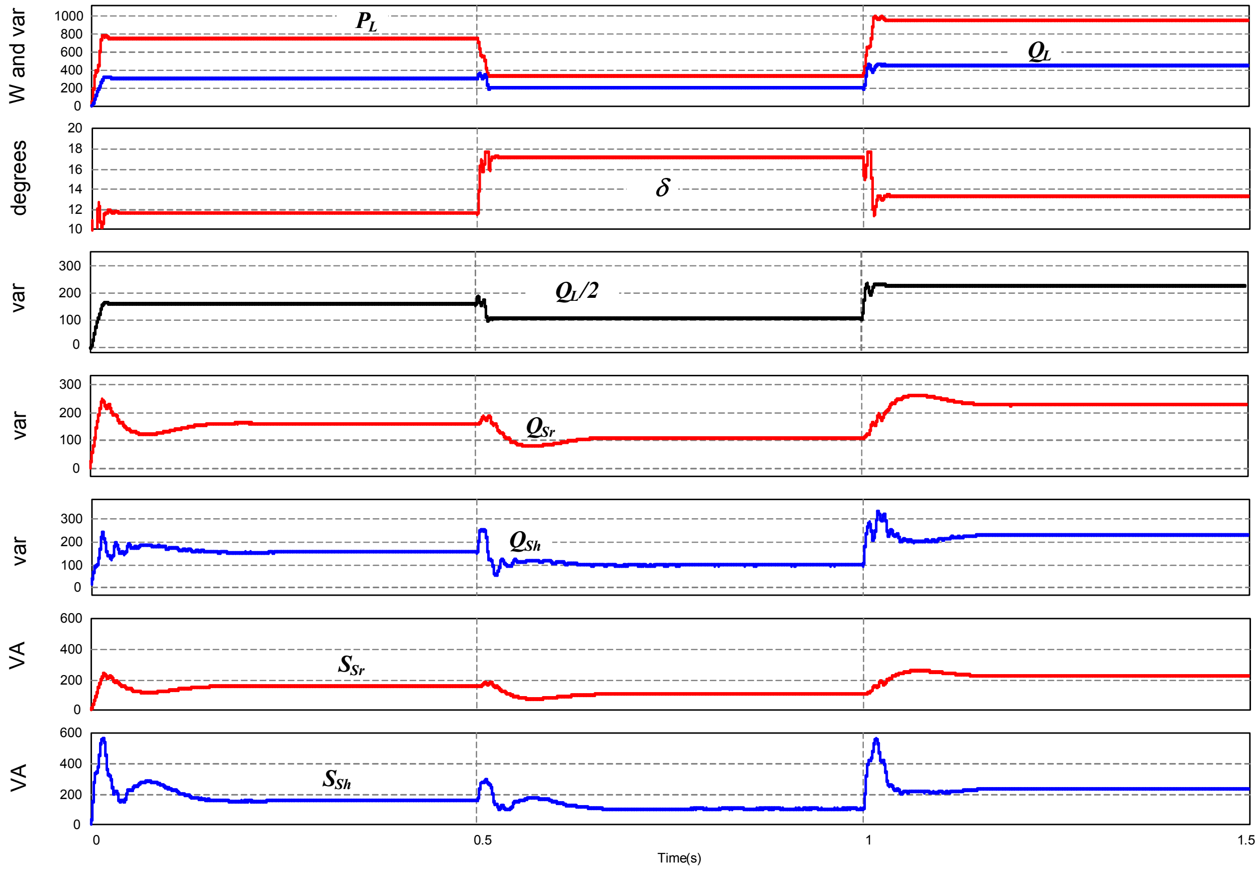

Fig. 9 – Measures of P_L, Q_L, δ, $1/2\,Q_L$, Q_{Sr} , Q_{Sh} , S_{Sr} , S_{Sh} depending on loads changes.

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