Universal Power Quality Conditioner based on Synchronous Reference Frame Theory for all Power Quality Problems Compensation

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Abstract: *the unified (or universal) power quality conditioner (UPQC), a combination of shunt and series active power filter, is mainly designed for voltage and current harmonics mitigation in distribution power system. This paper proposes a convenient control of this device in such away to compensate major power system disturbances such as: voltage and current harmonics, voltage sags and swells, voltage interruption, voltage and current unbalance and reactive power. The proposed control strategy is based on The Synchronous dq0 reference frame method to generate the voltage and current references. According to these references, the series and parallel converters of UPQC inject the appropriate voltage or current in the power system using PWM control technique. Simulation results using MATLAB / SIMULINK are presented to validate this control strategy and corresponding performance of the UPQC.*

Keywords: *UPQC, Synchronous reference frame, PWM control technique, power system disturbances.*

1. INTRODUCTION

The recent proliferation of energy-efficient solid-state semiconductor switches in nonlinear electrical loads such as arc furnaces, rectifiers, adjustable speed drives, etc, has increased the amount of voltage and current distortion in power distribution systems. Nonlinear loads draw from the power grid reactive power and current harmonics, which can cause power factor penalties, harmonic interference, and voltage distortion [1]. To mitigate voltage and current harmonics, active power filters are used. Active power filters can be classified as series or parallel by their system configuration. The combination of series and parallel active power filters is called the Unified Power Quality Conditioner (UPQC).

Faults at either the transmission or distribution level may cause voltage sag or swell in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Voltage sags can occur at any instant of time, with amplitudes ranging from 10 – 90% and a duration lasting for half a cycle to one minute [2]. Further, they could be either balanced or unbalanced, depending on the type of fault and they could have unpredictable magnitudes, depending on factors such as distance from the fault and the transformer connections. Voltage swell, is defined as a sudden increasing of supply voltage up 110% to 180% in RMS voltage at the network fundamental frequency with duration from half a cycle to 1 minute [2]. Voltage sag and swell can cause sensitive equipment (such as found in semiconductor or chemical plants) to fail, or shutdown, as well as create a large current unbalance that could blow fuses or trip breakers. These effects can be very expensive for the customer, ranging from minor quality variations to production downtime and equipment damage [3]. There are many different methods to mitigate voltage sags and swells, but the most important one is the use of Dynamic Voltage Restorer (DVR) [4].

To solve these problems all together only with one device, the unified power quality conditioner (UPQC) is proposed. Although, its main function is to mitigate the system current and voltage harmonics [5]; it can be controlled conveniently to offer not only harmonics elimination but also compensation for reactive power, load current unbalance, source voltage sags and swells, source voltage unbalance and power factor correction [6]. This paper therefore proposes the concept of combining the basic functions of UPQC (compensation of harmonics) with the compensation of other current and voltage disturbances. So, the device based on this concept could be called Universal Power Quality Conditioner, as it is intended to compensate major Power System Disturbances originated both from the load side and from the supply source side. Finally, to confirm the proposed concept, simulation using MATLAB-SIMULINK has been carried out and the results are illustrated and discussed.

2. UPQC AND THE BASIC OPERATION

Figure 1 shows the general structure of an UPQC with the combination of a series and shunt active filters. Unified Power Quality Conditioner (UPQC) can compensate: supply voltage sag or swell, voltage and current unbalance or harmonics and reactive. UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems.

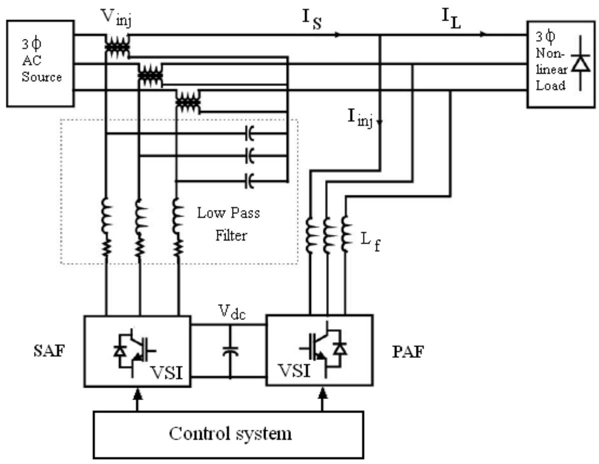

Fig.1. UPQC general structure

A. Series Active Filter (SAF)

It is connected in series with the incoming utility supply through a low pass filter and a voltage injecting transformer (Figure 1). The low pass filter eliminates the high switching frequency ripple of the inverter. The filter may inject some phase shift, which could be load dependent, but suitable feedback control is designed to dynamically adjust this shift. SAF is responsible for compensating the deficiency in voltage quality of the incoming supply; such that the load end voltage remains insensitive to the variation of utility supply.

B. Parallel Active Filter (PAF)

It is connected in parallel with the nonlinear load through a boost inductor L_f, which can boost up the common dc link voltage to the desired value through appropriate control. The size of the inductor has to be chosen carefully, bigger size would cause slower response to current control and smaller size would cause the high switching frequency ripple of the inverter to be injected into the distribution system. The main purpose of the PAF is to provide required Var support to the load, and to suppress the load current harmonics from flowing towards the utility.

DC-link capacitor C provides the common DC-link voltage to both SAF and PAF. Ideally once charged, the dc link voltage should not fall off its charge, but due to finite switching losses of the inverters, inductors and capacitors, some active power is consumed and the charge of the dc link voltage needs to be maintained in a closed loop control, through the PAF.

C. Control System

The aim of the control system is to maintain source current and load voltage profile sinusoidal and at rated value. The control system of the general configuration typically consists of a voltage and current reference generation method which determines the reference voltage or current that should be injected by SAF or PAF and the VSI control which is in this work consists of PWM with PI controller. The controller input is an error signal obtained from the reference voltage or current and the value of the injected voltage or current (Figure 2). Such error is processed by a PI controller then the output is provided to the PWM signal generator that controls the voltage source inverter (VSI) to generate the required injected voltage or current.

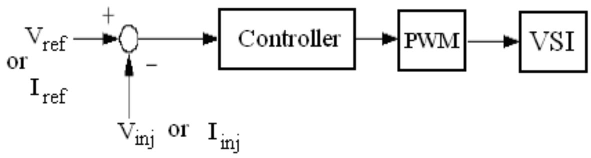

Fig.2. VSI control principle

D. PI controller

The reason behind the extensive use of proportional integral (PI) controller is its effectiveness in the control of steady-state error of a control system and also its easy implementation. However, one disadvantage of this conventional compensator is the difficulty in tuning its gains. The conventional PI controller (Figure 3) has the form of Eq. (1), where U is the control output which is fed to the PWM signal generator. K_P and K_I are the proportional and integral gains respectively, these gains depend on the system parameters. ε is the error signal, which is the difference of the injected voltage or current to the reference voltage or current.

$$U(t) = K_P \varepsilon(t) + K_I \int_T \varepsilon(t) d(t) \quad (1)$$

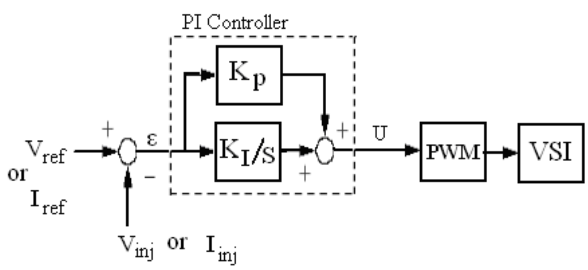

Fig.3. Control of the injected voltage or current using PI controller

E. Current and voltage Reference Generation

Several control methods involved in generating reference signals have been discussed in literature among them being the Synchronous d-q-0 Reference Frame method (SRF) [7, 8]. This method is based on the transformation of the currents or voltages in a-b-c frame to synchronously rotating d-q-0 frame. Figure 4 explains the basic building blocks of the method and its implementation in MATLAB / SIMULINK. The DC-Link voltage regulation is done by PAF through SRF method as it is shown in figure 4. Voltage Reference for the series active filter can be determined based almost on the same procedure [9]. Figure 5 gives the block diagram in MATLAB / SIMULINK representation for voltage reference generation.

The abc_to_dq0 Transformation block computes the direct axis, quadratic axis, and zero sequence quantities in a two-axis rotating reference frame for a three-phase sinusoidal signal. The following transformation is used:

$$i_d = \frac{2}{3}(i_a \sin(\omega t) + i_b \sin(\omega t - 2\pi/3) + i_c \sin(\omega t + 2\pi/3))$$
$$i_q = \frac{2}{3}(i_a \cos(\omega t) + i_b \cos(\omega t - 2\pi/3) + i_c \cos(\omega t + 2\pi/3))$$
$$i_0 = \frac{1}{3}(i_a + i_b + i_c) \qquad (2)$$

Where ω = rotation speed (rad/s) of the rotating frame.

The reference frame is synchronized with the ac currents, and is rotating at the same frequency (ω=2πf). The angle of the transformation is detected by using a phase locked loop (PLL). i_0 is the zero sequence component which is equal to zero in 3-phase 3-wire balanced system, i_d and i_q are made up of a DC and an AC component, so that they may be expressed by:

$$i_d = \bar{i_d} + \tilde{i_d} \qquad (3)$$

$$i_q = \bar{i_q} + \tilde{i_q} \qquad (4)$$

$\bar{i_d}$ and $\bar{i_q}$ are DC components due to fundamental currents. $\tilde{i_d}$ and $\tilde{i_q}$ are AC components due to harmonic currents. In order to compensate reactive power and eliminate harmonic currents, the AC component of i_d is to be fed by PAF, while i_q must be fully fed by the PAF because it is also possible in this way to achieve reactive power compensation. The AC part of i_d is due to harmonic components, so if it is fed to the load by the PAF, grid current remains sinusoidal, while the load keeps on receiving the same amount of harmonic and fundamental current. AC and DC components can be separated by a low pass filter. To return back into a-b-c frame, the following transformation is used:

$$i_a = i_d \sin(\omega t) + i_q \cos(\omega t) + i_0$$
$$i_b = i_d \sin(\omega t - 2\pi/3) + i_q \cos(\omega t - 2\pi/3) + i_0$$
$$i_c = i_d \sin(\omega t + 2\pi/3) + i_q \cos(\omega t + 2\pi/3) + i_0 \qquad (5)$$

One of the most important characteristics of this method is that the reference currents are obtained directly from the loads currents without considering the source voltages. This is an important advantage since the generation of the reference signals is not affected by voltage distortion, so, increasing the compensation robustness and performance.

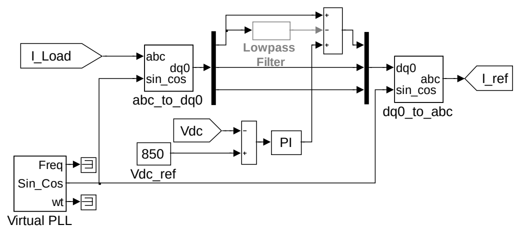

Fig.4. SIMULINK Implementation of SRF method for current reference generation.

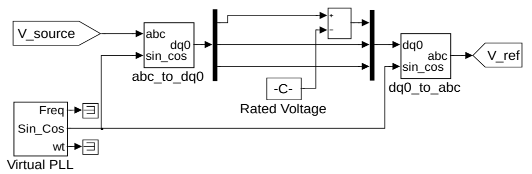

Fig.5. SIMULINK Implementation of SRF method for voltage reference generation

3. SIMULATION RESULTS AND DISCUSSION

The proposed system configuration of Figure 1 has been simulated by MATLAB/SIMULINK as it is shown in Figure 6.

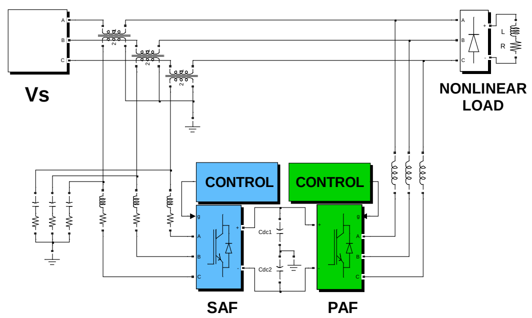

Fig.6. MATLAB/SIMULINK model for the studied system configuration.

The task of this simulation is to evaluate the performance of the UPQC in steady and transient state conditions in various cases that UPQC can face. So, five cases of voltage source (equivalent of power system at PCC) state have been executed in simulation. These cases are respectively; no voltage disturbance, voltage swell, voltage harmonics, voltage sag and voltage unbalance. The source is feeding a nonlinear load which generates current harmonics. For the sake of simplicity and clarity, only one phase is shown (phase a) for discussion of the results. To confirm that we are dealing with three phase system, simulation of the five cases together of the three phase system has been given in figure 8.

In the following simulations, the main characteristics of the UPQC are set as: voltage source full-bridge IGBT based inverter controlled with PWM signal generator with commutation frequency of 12 kHz, capacitor energy storage bank 10 mF, coupling transformer ratio 1:1, nominal dc link voltage 850 V, phase voltage 220 V and source frequency of 50 Hz. The load consists of non linear load of 80 kVA. The control of the injected harmonic currents and voltages is done by a conventional PI controller. The simulation results are shown in Figures 7, 8, and 9. From figures 7 and 8 we can observe:

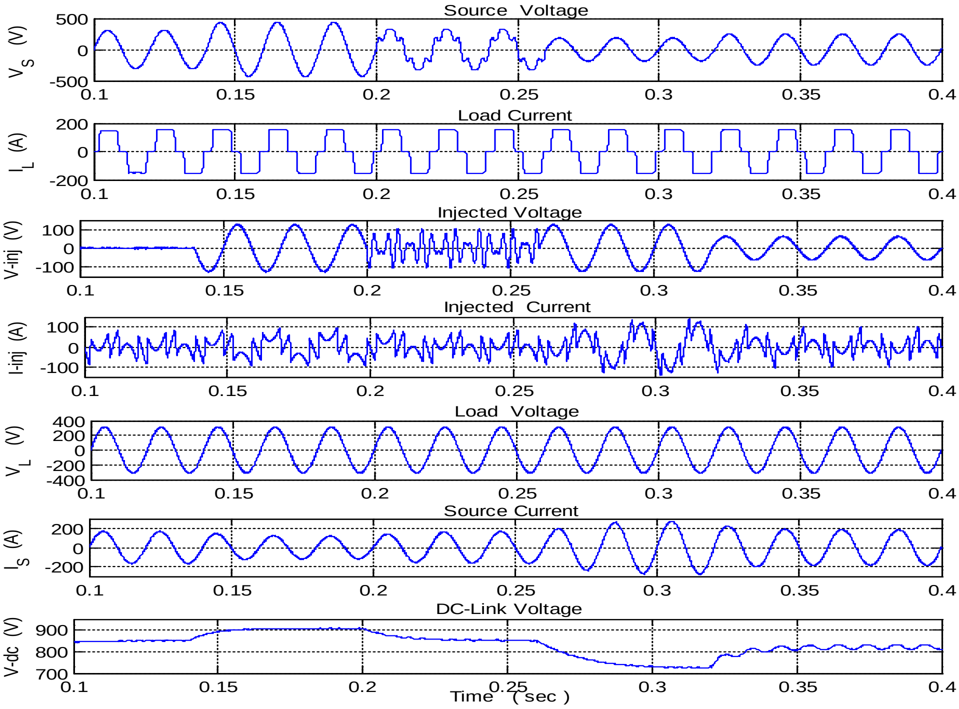

Fig.7. Compensation of source voltage sag and swell, source voltage unbalance, source voltage harmonics and load current harmonics for one phase (phase a)

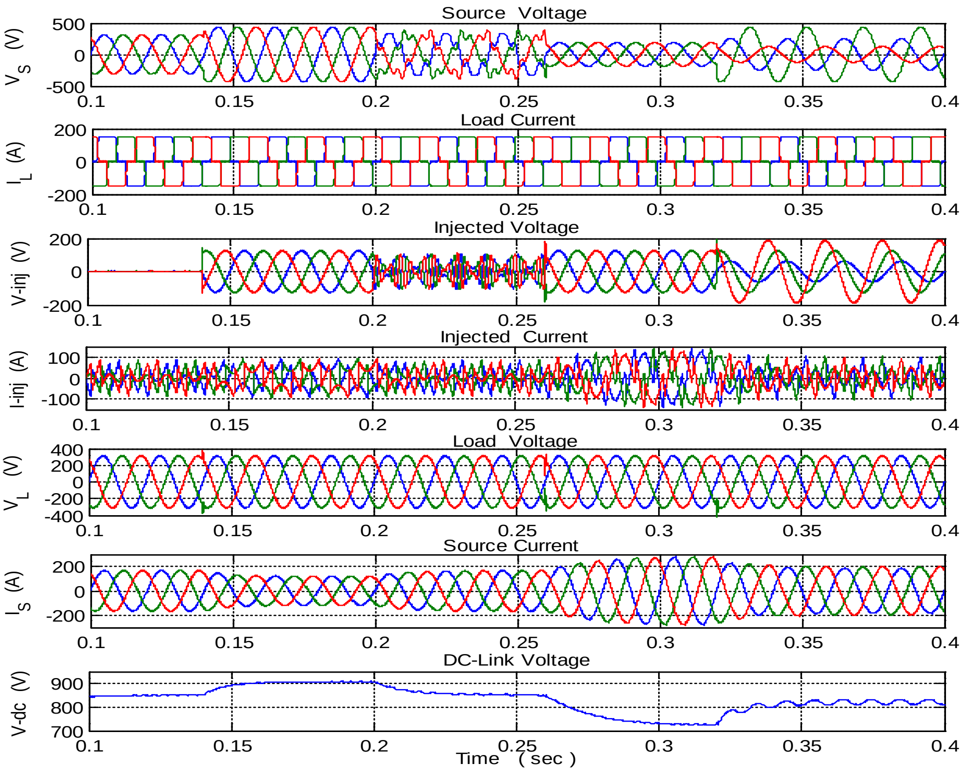

Fig.8. Compensation of source voltage sag and swell, source voltage unbalance, source voltage harmonics and load current harmonics for three phase system.

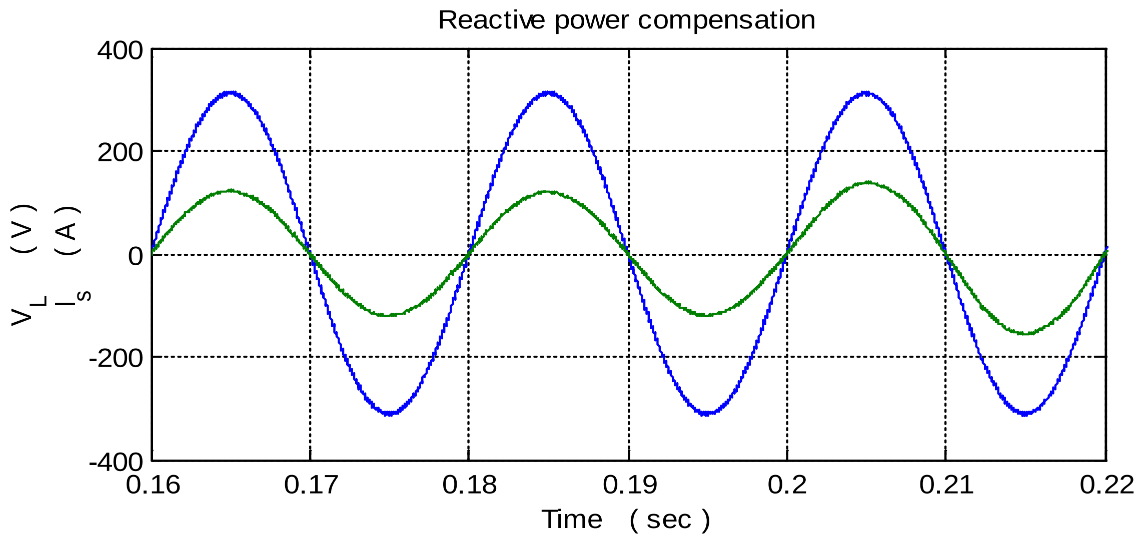

Fig.9. Compensation of reactive power absorbed by the non linear load.

1st case: no voltage disturbance (0.1s -- 0.14 s)

In this case, UPQC has compensated only the load harmonic currents. So, only the shunt part (PAF) was working while the series part was in standby mode. PAF has injected harmonic currents of order 6k ± 1 (k natural number) making the source current distortion passes from THD = 26.89% to THD= 0.88% with a magnitude of the fundamental current of 166.6 A. The active power needed to compensate current harmonics is very small (theoretically is zero) that's why the regulation of the DC-Link voltage stays stable at the reference voltage (850 V).

2nd case: 40% voltage swell (0.14 s – 0.2 s)

In this case, UPQC has compensated load current harmonics and source voltage swell. Thus, the two parts were working (SAF and PAF) simultaneously. SAF has injected the appropriate voltage to keep the load voltage at its rated value with negligible distortion (THD = 0.58%). PAF has injected harmonic currents making the source current distortion passes from THD = 26.89% to THD= 1.69% with a magnitude of the fundamental current of 125.4 A. The decrease in source current is due to the transfer of a part of voltage swell to a load current by UPQC through DC-Link capacitor. The DC-Link voltage increases to 906 V because the voltage swell has been absorbed by the DC-Link capacitor through SAF.

3rd case: voltage harmonics (0.2 s – 0.26 s).

In this case, UPQC has compensated the source voltage and the load current harmonics thus, SAF has injected the fifth and the seventh harmonics of amplitude (20%) and (14%) respectively, and also PAF has injected current harmonics of order 6k ± 1 (k natural number) which are generated by the nonlinear load. The THD of the source voltage was 24.62% and after compensation the load voltage THD becomes 0.56%, also The THD of the load current was 26.89% and after compensation the source current THD becomes 1.46% with a magnitude of the fundamental current of 158.9 A. The DC-link voltage returns to its reference value and remains almost stable at 850 V with negligible oscillations (< 1%).

4th case: 40% voltage sag (0.26 s – 0.32 s).

In this case, UPQC has compensated load current harmonics and source voltage sag. Thus, the two parts were working (SAF and PAF) simultaneously. SAF has injected the appropriate voltage to keep the load voltage at its rated value with negligible distortion (THD = 0.50%). PAF has injected harmonic currents making the source current distortion passes from THD = 26.89% to THD= 2.01% with a magnitude of the fundamental current of 250.1 A. The increase in source current is due to the transfer of a part of source current to a load voltage by UPQC through DC-Link capacitor. The DC-Link voltage drops to 725 V because the capacitor is asked to deliver an important active power in a form of voltage to compensate the source voltage sag. This drop in DC-Link voltage is 14.70% which is acceptable since UPQC still work properly; but if we want to compensate more voltage sag (>40%) we have to increase the capacitance of the capacitor to avoid this drop.

5th case: voltage unbalance (0.32 s – 0.4 s).

In this case, UPQC has compensated load current harmonics and source voltage unbalance (phase a: 20% sag, phase b: 40% swell and phase c: 60% sag). Thus, the two parts were working (SAF and PAF) simultaneously. SAF has injected the appropriate voltage to keep the load voltage at its rated value with negligible distortion (THD = 0.54%). PAF has injected harmonic currents making the source current distortion passes from THD = 26.89% to THD= 2.69% with a magnitude of the fundamental current of 199.3 A. The increase in source current is due to the transfer of a part of source current to a load voltage by UPQC through DC-Link capacitor. The DC-Link voltage oscillates between 830 V and 810 V because the capacitor is asked to deliver active power in a form of voltage to compensate the source voltage unbalance. This drop in DC-Link voltage is between 4.7% and 2.3% which is very acceptable since UPQC still work properly; but if we want to compensate more voltage unbalance we have to increase the capacitance of the capacitor to avoid this drop.

Figure 9 shows the ability of UPQC to compensate also the reactive power absorbed by the load since we can see clearly that the current and the voltage are in phase (no lag or lead). Finally, from these simulations, it is clear and obvious that UPQC can be used as universal power quality conditioner since it has the ability to compensate the majority of power quality problems.

4. CONCLUSION

This paper presented the UPQC (Unified Power Quality Conditioner), which consists of series and parallel active power filter. The control strategy was derived based on the synchronous reference frame method, thus enabling the easy filtering and flexible control implementation. The proposed control method allowed UPQC to compensate voltage and current harmonics, voltage sag and swell, voltage and current unbalance, voltage interruption and reactive power. The operation and the effectiveness of the proposed system were verified through simulations using MATLAB/SIMULINK software. Simulation results showed that balanced and almost sinusoidal input currents and output voltages with low THD can be obtained under all conditions.

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