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Power quality improvement by using multi converter unified power quality conditioning system

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Abstract

In order to meet PQ standard limits, it may be necessary to include some sort of compensation. Modern solutions can be found in the form of active rectification or active filtering. A shunt active power filter is suitable for the suppression of negative load influence on the supply network, but if there are supply voltage imperfections, a series active power filter may be needed to provide full compensation. In recent years, solutions based on flexible ac transmission systems (FACTS) have appeared. The application of FACTS concepts in distribution systems has resulted in a new generation of compensating devices. A unified power quality conditioner (UPQC) is the extension of the unified power-flow controller (UPFC) concept at the distribution level. It consists of combined series and shunt converters for simultaneous compensation of voltage and current imperfections in a supply feeder. An IPFC consists of two series VSCs whose dc capacitors are coupled. This allows active power to circulate between the VSCs. With this configuration, two lines can be controlled simultaneously to optimize the network utilization. An interline unified power-quality conditioner (IUPQC), which is the extension of the IPFC concept at the distribution level. This paper presents a new unified power-quality conditioning system (MC-UPQC), capable of simultaneous compensation for voltage and current in multi-bus/multi-feeder systems. In this configuration, one shunt voltage-source converter (shunt VSC) and two or more series VSCs exist. The system can be applied to adjacent feeders to compensate for supply-voltage and load current imperfections on the main feeder and full compensation of supply voltage imperfections on the other feeders.

Keywords: Interline Unified Power Quality Conditioner, Multi Converter Unified Power Quality Conditioner, Power Quality, Sag, Swell, Unified Power Quality Conditioner, Unified Power Flow Controller, Voltage Source Converter

1. Introduction

In recent years, solutions based on flexible ac transmission systems (FACTS) have appeared. The application of FACTS concepts in distribution systems has resulted in a new generation of compensating devices. A unified power-quality conditioner (UPQC) is the extension of the unified power-flow controller (UPFC) concept at the distribution level. It consists of combined series and shunt converters for simultaneous compensation of voltage and current imperfections in a supply feeder.

Recently, multi converter FACTS devices, such as an Interline power-flow controller (IPFC) and the generalized Unified power-flow controller (GUPFC) are introduced. The aim of these devices is to control the power flow of multiline or a sub network rather than control the power flow of a single line by, for instance, a UPFC.

2. Power Quality

With increasing applications of nonlinear and electronically switched devices in distribution systems and industries, power-quality (PQ) problems, such as harmonics, flicker, and imbalance have become serious concerns. In addition, lightning strikes on transmission lines, switching of capacitor banks, and various network faults can also cause PQ problems, such as transients, voltage sag/swell, and interruption. On the other hand, an increase of sensitive loads involving digital electronics and complex process controllers requires a pure sinusoidal supply voltage for proper load operation.

In order to meet PQ standard limits, it may be necessary to include some sort of compensation. Modern solutions can be found in the form of active rectification or active filtering. A shunt active power filter is suitable for the suppression of negative load influence on the supply network, but if there are supply voltage imperfections, a series active power filter may be needed to provide full compensation

Power Quality Problems

For the purpose of this article, we shall define power quality problems as:

‘Any power problem that results in failure or misoperation of customer equipment manifests itself as an economic burden to the user, or produces negative impacts on the environment.’

When applied to the container crane industry, the power issues which degrade power quality include:

- Power Factor
- Harmonic Distortion
- Voltage Transients
- Voltage Sags or Dips
- Voltage Swells

The AC and DC variable speed drives utilized on board container cranes are significant contributors to total harmonic current and voltage distortion. Whereas SCR phase control creates the desirable average power factor, DC SCR drives operate at less than this. In addition, line notching occurs when SCR’s commutate, creating transient peak recovery voltages that can be 3 to 4 times the nominal line voltage depending upon the system impedance and the size of the drives. The frequency and severity of these power system disturbances varies with the speed of the drive. Harmonic current injection by AC and DC drives will be highest when the drives are operating at slow speeds. Power factor will be lowest when DC drives are operating at slow speeds or during initial acceleration and deceleration periods, increasing to its maximum value when the SCR’s are phased on to produce rated or base speed. Above base speed, the power factor essentially remains constant. Unfortunately, container cranes can spend considerable time at low speeds as the operator attempts to spot and land containers. Poor power factor places a greater kVA demand burden on the utility or engine-alternator power source. Low power factor loads can also affect the voltage stability which can ultimately result in detrimental effects on the life of sensitive electronic equipment or even intermittent malfunction. Voltage transients created by DC drive SCR line notching, AC drive voltage chopping, and high frequency harmonic voltages and currents are all significant sources of noise and disturbance to sensitive electronic equipment

Power quality can be improved through:

- Power factor correction,
- Harmonic filtering,
- Special line notch filtering,
- Transient voltage surge suppression,
- Proper earthing systems.

3. Unified Power Quality Conditioner

The provision of both DSTATCOM and DVR can control the power quality of the source current and the load bus voltage. In addition, if the DVR and STATCOM are connected on the DC side, the DC bus voltage can be regulated by the shunt connected DSTATCOM while the DVR supplies the required energy to the load in case of the transient disturbances in source voltage. The Unified Power Quality Conditioner is a versatile device similar to a UPFC. However, the control objectives of a UPQC are quite different from that of a UPFC.

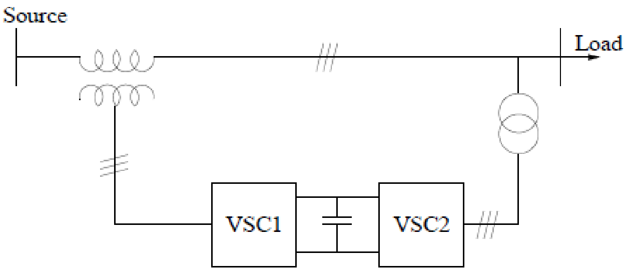

Fig 1: Unified Power Quality Conditioner

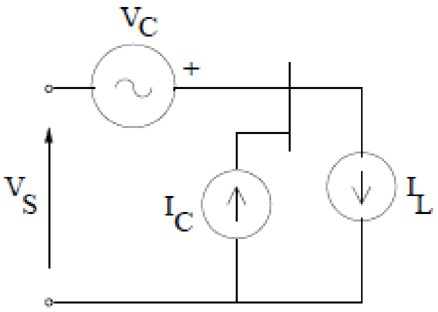

Fig 2: UPQC Idealized Equivalent Circuit

The operation of a UPQC can be explained from the analysis of the idealized equivalent circuit. Here, the series converter is represented by a voltage source VC and the shunt converter is represented by a current source IC. Note that all the currents and voltages are 3 dimensional vectors with phase coordinates. Unlike in the case of a UPFC, the voltages and currents may contain negative and zero sequence components in addition to harmonics. Neglecting losses in the converters, we get the relation

$$\langle V_L, I_C \rangle + \langle V_C, I_S \rangle = 0$$

Where X, Y denote the inner product of two vectors, defined by

$$\langle X, Y \rangle = \frac{1}{T} \int_0^T X^t(\tau) Y(\tau) d\tau .$$

Let the load current IL and the source voltage VS be decomposed into two Components given by

$$I_L = I_L^{1p} + I_L^r$$

$$V_S = V_S^{1p} + V_S^r$$

Where IL1p contains only positive sequence, fundamental frequency components. Similar comments apply to V 1pS .IrL and V rS contain rest of the load current and the source voltage including harmonics. I1pL is not unique and depends on the power factor at the load bus. However, the following relation applies for I1p L.

$$P_L = \langle V_L, I_L \rangle = \langle V_L, I_L^{1p} \rangle$$

This implies that hIrL; VLi = 0. Thus, the fundamental frequency, positive sequence component in IrL does not contribute to the active power in the load. To meet the control objectives, the desired load voltages and source currents must contain only positive sequence, fundamental frequency components and

$$P_L = |V_L^* \; I_S^*| \cos \phi_l = |V_S^{1p} I_S^*| \cos \phi_s$$

Where V ¤ L and I¤S are the reference quantities for the load bus voltage and the source current respectively. Àl is the power factor angle at the load bus while Ás is the power factor angle at the source bus (input port of UPQC). Note that V¤L (t) and I¤S (t) are sinusoidal and balanced. If the reference current (I¤C) of the shunt converter and the reference voltage (V¤C) of the series converter are chosen as

$$I_C^* = I_L^*, \quad V_C^* = -V_S^r + V_C^{1p}$$

With the constraint

$$\langle V_C^{1p}, I_S^* \rangle = 0$$

We have,

$$I_S^* = I_L^{1p}, \quad V_L^* = V_S^{1p} + V_C^{1p}$$

Note that the constraint implies that V 1p C is the reactive voltage in quadrature with the desired source current, IS. It is easy to derive that $\langle V_C^*, I_S^* \rangle = 0 = \langle I_C^*, V_L^* \rangle$ the above equation shows that for the operating conditions assumed, a UPQC can be viewed as inaction of a DVR and a STATCOM with no active power own through the DC link. However, if the magnitude of V to be controlled, it may not be feasible to achieve this by injecting only reactive voltage. The situation gets complicated if V 1pS is not constant, but changes due to system disturbances or fault. To ensure the regulation of the load bus voltage it may be necessary to inject variable active voltage (in phase with the source current). If we express

$$V_C = V_C^* + \Delta V_C, I_C = I_C^* + \Delta I_C$$

$$I_S = I_S^* - \Delta I_C, V_L = V_S^{1p} + V_C^{1p} + \Delta V_C$$

$$\langle I_S, \Delta V_C \rangle + \langle V_L, \Delta I_C \rangle = 0$$

In deriving the above, we assume that

$$\langle I_S, V_C^* \rangle = 0 = \langle V_L, I_C^* \rangle$$

This implies that both ¢VC and ¢IC are perturbations involving positive sequence, fundamental frequency quantities (say, resulting from symmetric voltage sags).the power balance on the DC side of the shunt and series converter. The perturbation in VC is initiated to ensure that

$$|V_C^* + \Delta V_C + V_S| = |V_L| = \text{constant}.$$

Proposed MC-UPQC System

The single-line diagram of a distribution system with an MC-UPQC is shown in Fig.

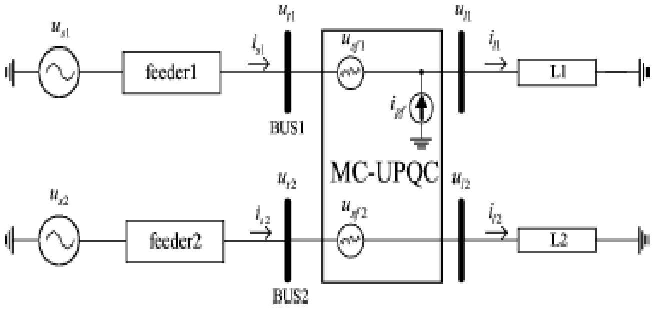

Fig 3: Single-line diagram of a distribution system with an MC-UPQC

As shown in this figure, two feeders connected to two different substations supply the loads L1 and L2. The MC-UPQC is connected to two buses BUS1 and BUS2 with voltages of u_{t1} and u_{t2}, respectively. The shunt part of the MC-UPQC is also connected to load L1 with a current of i_{l1}. Supply voltages are denoted by u_{s1} and u_{s2} while load voltages are u_{l1} and u_{l2}. Finally, feeder currents are denoted by i_{s1} and i_{s2} and load currents are i_{l1} and i_{l2}.Bus voltages u_{t1} and u_{t2} are distorted and may be subjected to sag/swell. The load L1 is a nonlinear/sensitive load which needs a pure sinusoidal voltage for proper operation while its current is non-sinusoidal and contains harmonics. The load L2 is a sensitive/critical load which needs a purely sinusoidal voltage and must be fully protected against distortion, sag/swell, and interruption. These types of loads primarily include production industries and critical service providers, such as medical centers, airports, or broadcasting centers where voltage interruption can result in severe economical losses or human damages.

MC–UPQC Structure

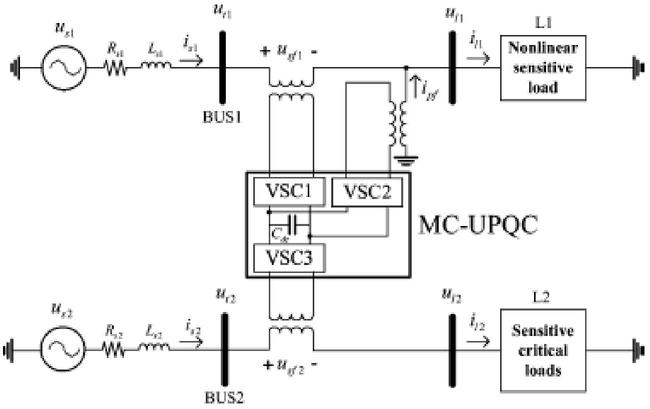

Fig 4: Typical MC-UPQC used in a distribution system.

It consists of three VSCs (VSC1, VSC2, and VSC3) which are connected back to back through a common dc-link capacitor. In the proposed configuration, VSC1 is connected in series withBUS1 and VSC2 is connected in parallel with load L1 at the end of Feeder1. VSC3 is connected in series with BUS2 at theFeeder2 end. Each of the three VSCs in Fig. 2 is realized by a three-phase converter with a commutation reactor and high-pass output filter

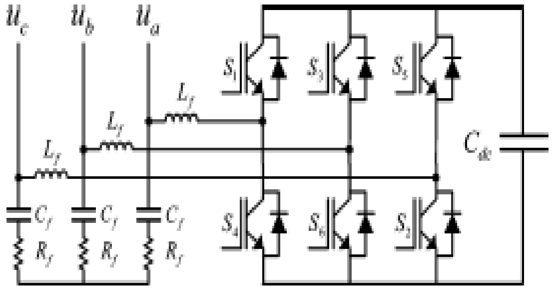

Fig 5: Schematic structure of VSC

Control Strategy

As shown in Fig., the MC-UPQC consists of two series VSCs and one shunt VSC which are controlled independently .The switching control strategy for series VSCs and the shunt VSC are selected to be sinusoidal pulse width-modulation (SPWM) voltage control and hysteresis current control, respectively. Details of the control algorithm, which are based on the d–q method [12], will be discussed later .Shunt-VSC: Functions of the shunt-VSC are:

1) To compensate for the reactive component of load L1 current;
2) To compensate for the harmonic components of load L1current;
3) To regulate the voltage of the common dc-link capacitor.

Fig. shows the control block diagram for the shunt VSC.

The measured load current (i_{l_abc}) is transformed into the synchronous dq0reference frame by using

$$i_{l\_dq0} = T_{abc}^{dq0}\, i_{l\_abc}.$$

Where the transformation matrix is shown in (2), at the bottom of the page.

By this transform, the fundamental positive-sequence component which is transformed into dc quantities in the d and q axes can be easily extracted by low-pass filters (LPFs). Also, all harmonic components are transformed into ac quantities with a fundamental frequency shift

$$\begin{aligned} i_{l\_d} &= \bar{i}_{l\_d} + \tilde{i}_{l\_d} \\ i_{l\_q} &= \bar{i}_{l\_q} + \tilde{i}_{l\_q} \end{aligned}$$

Where

i_{l_d}, i_{l_q} are d-q components of load current,

$\bar{i}_{l\_d}, \bar{i}_{l\_q}$ are dc components, and

$\bar{i}_{l\_d}, \bar{i}_{l\_q}$ are the ac components of $\bar{i}_{l\_d}, \bar{i}_{l\_q}$.

If i_s is the feeder current and i_{pf} is the shunt VSC current and knowing $i_s = i_l - i_{\mathrm{pf}}$, then d–q components of the shunt VSC reference current are defined as follows:

$$\begin{aligned} i_{pf\_d}^{\mathrm{ref}} &= \tilde{i}_{l\_d} \\ i_{pf\_q}^{\mathrm{ref}} &= i_{l\_q}. \end{aligned}$$

Consequently, the d–q components of the feeder current are

$$i_{s\_d} = \bar{i}_{l\_d}$$

$$i_{s\_q} = 0.$$

This means that there is no harmonic and reactive component sin the feeder current. Switching losses cause the dc-link capacitor voltage to decrease. Other disturbances, such as the sudden variation of load, can also affect the dc link. In order to regulate the dc-link capacitor voltage, a proportional–integral (PI) controller is used as shown in Fig. The input of the PI controller is the error between the actual capacitor voltage (u_{dc}) and its reference value (u_{dc}^{ref}). The output of the PI controller (i.e., Δi_{dc} is added to the d component of the shunt-VSC reference current to form a new reference current as follows:

$$\begin{cases} i_{pf\_d}^{\mathrm{ref}} = \tilde{i}_{l\_d} + \Delta i_{dc} \\ i_{pf\_q}^{\mathrm{ref}} = i_{l\_q} \end{cases}$$

As shown in Fig., the reference current in (9) is then transformed back into the abc reference frame. By using PWM hysteresis current control, the output-compensating currents in each phase are obtained

$$i_{pf\_abc}^{\mathrm{ref}} = T_{dq0}^{abc}\, i_{pf\_dq0}^{\mathrm{ref}}; \; (T_{dq0}^{abc} = {T_{abc}^{dq0}}^{-1}).$$

4. Simulation Results

The proposed MC-UPQC and its control schemes have been tested through extensive case study simulations using PSCAD/ EMTDC. In this section, simulation results are presented, and the performance of the proposed MC-UPQC system is shown.

The MC–UPQC is switched on at t=0.02 s. The BUS1 voltage, the corresponding compensation voltage injected by VSC1, and finally load L1 voltage are shown in Fig.

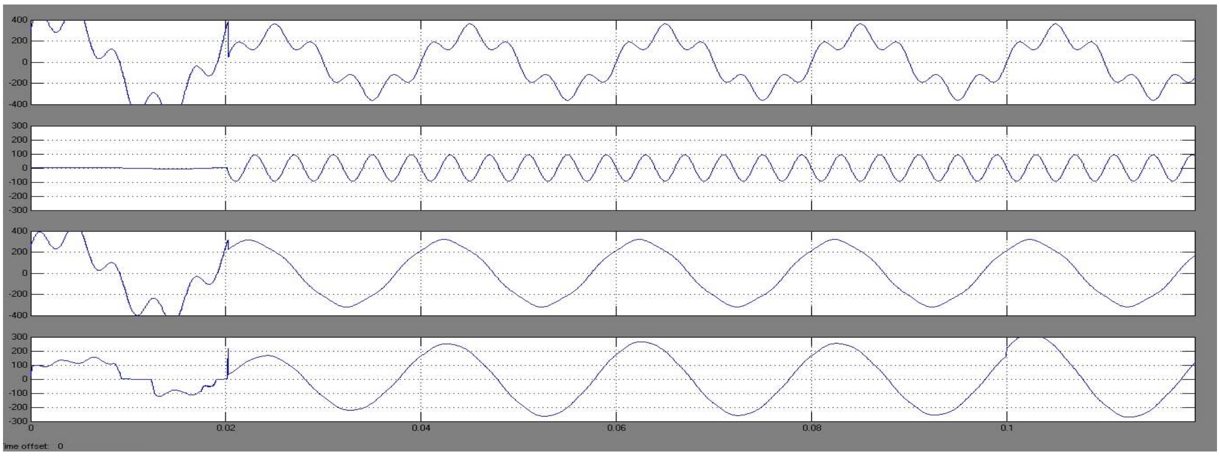

Fig 6: BUS 1 voltage, series compensating voltage, and load voltage in Feeder 1 and Feeder 2

In all figures, only the phase a waveform is shown for simplicity. Similarly, the BUS2 voltage, the corresponding compensation voltage injected by VSC3, and finally, the load L2 voltage are shown in Fig.

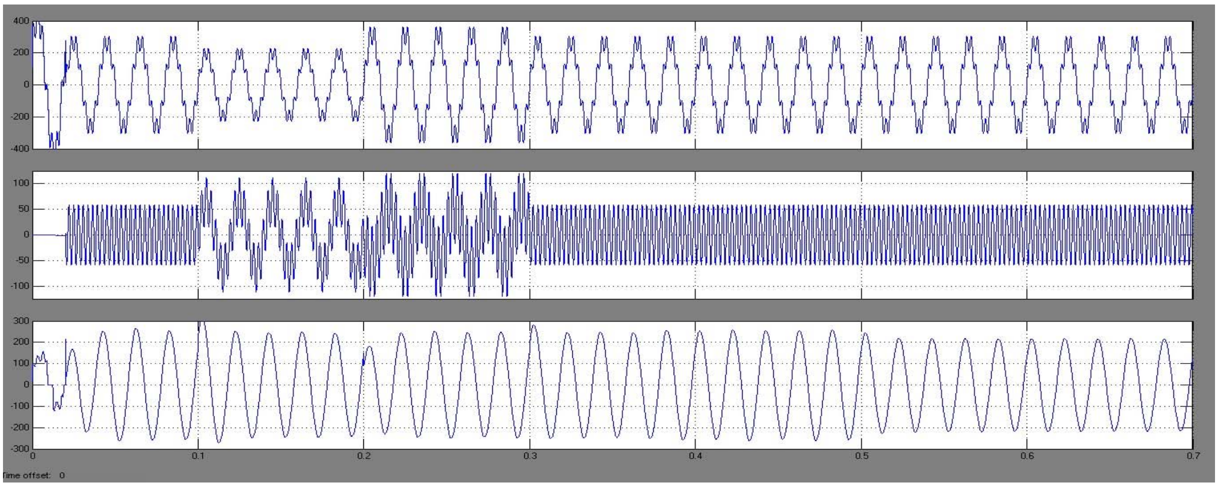

Fig 7: BUS 2 voltage, series compensating voltage, and load voltage in Feeder 2.

The performance of the MC-UPQC under a fault condition on Feeder2 is tested by applying a three-phase fault to ground on Feeder2 between 0.3s<t<0.4 s.

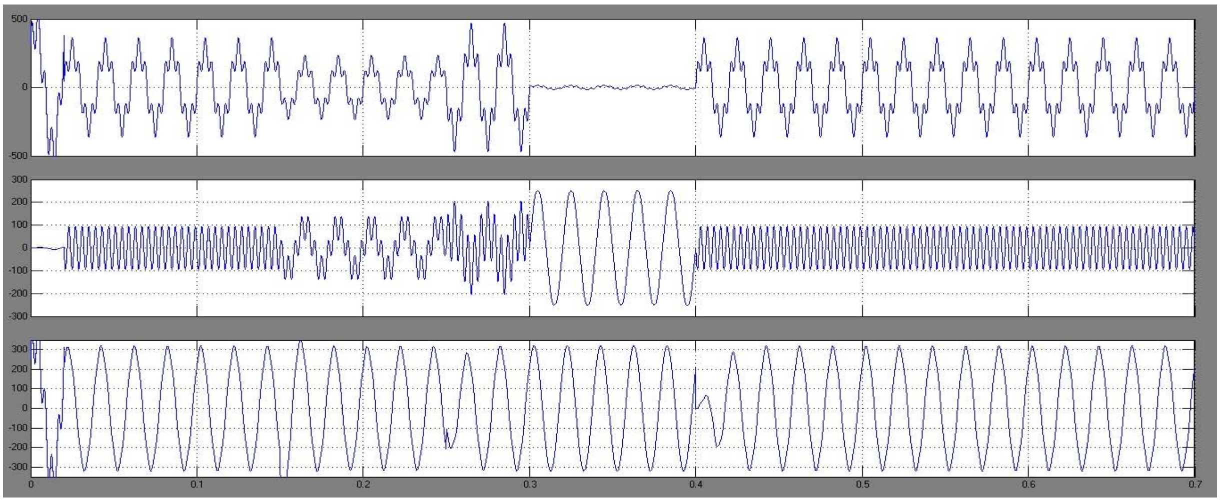

Fig 8: Simulation results for an upstream fault on Feeder2: BUS2 voltage, compensating voltage, and loads L1 and L2 voltages.

5. Conclusion

A new configuration for simultaneous compensation of voltage and current in adjacent feeders has been proposed. The new configuration is named multi-converter unified power-quality conditioner (MC-UPQC). Compared to a conventional UPQC, the proposed topology is capable of fully protecting critical and sensitive loads against distortions, sags/swell, and interruption in two-feeder systems. The idea can be theoretically extended to multibus/multifeeder systems by adding more series VSCs. The performance of the MC-UPQC is evaluated under various disturbance conditions and it is shown that the proposed MC-UPQC offers the following advantages:

- Power transfer between two adjacent feeders for sag/swell and interruption compensation.
- Compensation for interruptions without the need for a battery storage system and, consequently, without storage capacity limitation.
- Sharing power compensation capabilities between two adjacent feeders and increasing the power quality of a system by compensating the voltage and current imperfections

6. References

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