Distribution System Disturbances and its Effects on Voltage Source Inverter Drives

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Abstract

Distribution system power capacities have increased in recent years to keep pace with the expansion and consolidation of many industrial facilities. At the same time the usage of VSI (Voltage Source Inverter) drives for increased power efficiency has also occurred. The employment of these drives has primarily taken place at the lower end of the horsepower spectrum, leaving many higher horsepower 3 phase motors still operating directly off the 3 phase distribution system. There are several predominate sources of disturbance which can effect the quality of the voltage waveforms on a poly phase power distribution system. The foremost are as follows:

- Lightning strike.
- Phase fault.
- Switching Capacitors (PFC Kvars).
- Across line starting 3 phase motors.

The primary focus of this paper will be to review the transient power distribution system effects of switching power factor correction capacitors and the ramifications for VSI drives.

Introduction

Lagging Kvars due to the prevalence of large inductive loads has the negative effect of increased energy cost, due to penalties imposed by the utility, higher system losses, due to reactive power losses and lower utilization power due to the previously mentioned losses. There are several methods available today to attempt to offset the lagging Kvars imposed by inductive power loads. The two most common methods for improving power factor is the use of shunt capacitors or synchronous motors. Over excitation of a synchronous motor will supply excess Kvars in order to compensate for other lagging Kvar loads on the system. Capacitors provide leading Kvars, usually sized to offset the lagging Kvars imposed by inductive loads. Capacitors are very economical to employ. There are immediate cost savings due to the removal of cost penalties by the utility and also due to the increase in system capacity because of the reduction of “reactive” power which was previously supported.

Power factor correction capacitors are most effectively applied when they are physically and electrically located close to the source of the lagging Kvars (induction motor) and are typically switched “on-line” with the motor load. When this is the case, care must be taken to insure motor torque transients are acceptable at power application and motor voltage levels are within reason at power removal A typical application, when the load consists of many lower power induction motor loads, has more of a distributed approach. Capacitors are centralized in a convenient location on the power bus and are switched in “as needed” in accordance with the sum of the motor loads in place. The usage of switched capacitors for the improvement of system power factor has one obvious immediate benefit to the industrial power consumer - lower utility costs. Other benefits which may be less apparent are an increase in distribution voltage and a real increase in total system capacity. But all is not free. There are some less apparent drawbacks to the use of switched capacitors on the power distribution system - voltage transients.

When a capacitor is switched onto the power distribution system, a momentary “short”: is imposed on the power bus causing a buildup of energy in the source leakage inductance and in the parasitic inductance's of the power bus. This

energy storage reveals itself as a voltage “ring up” on the phase voltage and can have negative effects on all electrical and electronic equipment used on the distribution system.

Distribution System Model

For the purpose of analyzing the effect of application of power factor correction capacitors for an industrial distribution system, the following simplified model of an industrial power distribution system is considered:

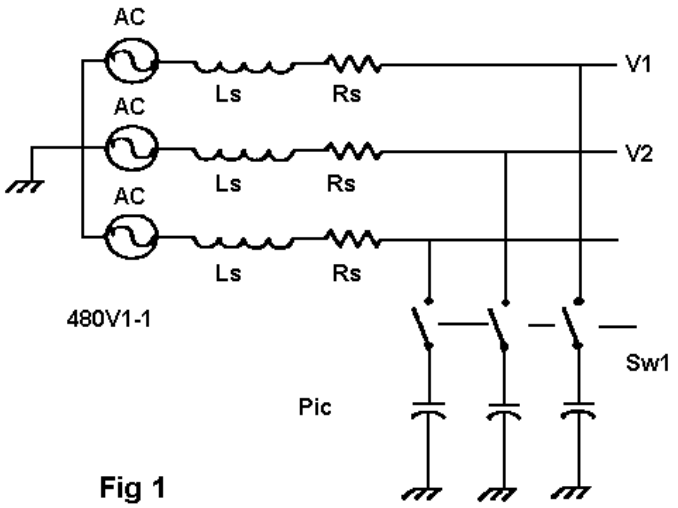

Fig 1

Given:

Ls = 33 uh / phase - source inductance
Rs = 0.01 ohms / phase - source resistance
Pfc = 900uf I phase - Correction capacitors Sw1 = Closes at peak H voltage.

(these are typical values for a 1MVA 480V system, with 6% source impedance and with 20% of the load as lagging reactive power)

This simplified schematic represents 2 phases of a typical 3 phase system with power factor capacitors connected in a line to neutral configuration. Spice simulation of the above circuit yields the following line to line voltage waveform at V1 - V2:

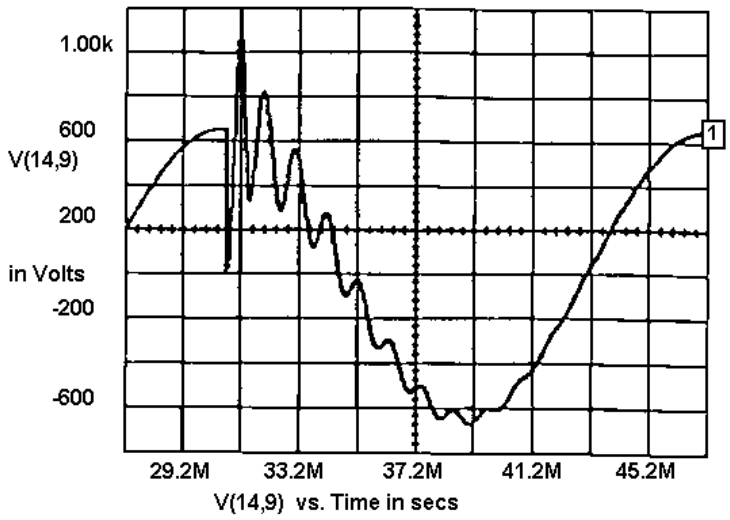

Fig 2

Depending on the parasitic inductance's and capacitance's on the distribution system, the magnitude of voltage “ring-up” on the 3 phase voltage can be as high as 2 times the fundamental voltage value. In the case of this example the peak voltage is approximately 11 00V, or 1.7 times the fundamental value. Also based on the values of source inductance, power factor correction Kvars and bus resistance, the typical waveform can be in the area of 500 to 2500Hz oscillation and can last for anywhere from a few hundred microseconds to tens of milli seconds. This simulation places the capacitor switching at the peak of the line to line voltage, which is a worse case condition. With a polyphase system, the probability of hitting the peak when 3 phases of capacitors are being applied is very high. Another item of interest is that if the series resistance is very low (i.e. the capacitors are switched at the secondary of the isolation transformer the circuit has a lower damping coefficient and the transient duration is increased. Placing PFC capacitors closer to the load will tend to increase the series resistance, therefore limiting the duration of the oscillation. The mathematics of the waveform in fig. 2 (V1 - V2) is given in the following:

$$V_{(t)} \equiv \frac{1}{C} \bullet \int_0^T E \bullet \frac{\exp(-aT)}{(w_d \bullet L)} \bullet \sin(w_d \bullet T) dt$$

$$a \equiv \frac{R}{2L} \equiv$$ Damping constant

$w_o := \equiv \frac{1}{\sqrt{L \bullet C}}$ Undamped resonant frequency r/s

$w_d := \equiv \sqrt{(w_o)^2 - a^2}$ Damped resonant frequency r/s

In the next section we will examine the impact this voltage transient has on a typical VSI drive**.**

Inverter Drive Integration

If the circuit of Fig**.** 1 is modified to add a rectifier converter for a typical small horsepower (5**-**30Hp) VSI drive the representative circuit would be as follows:

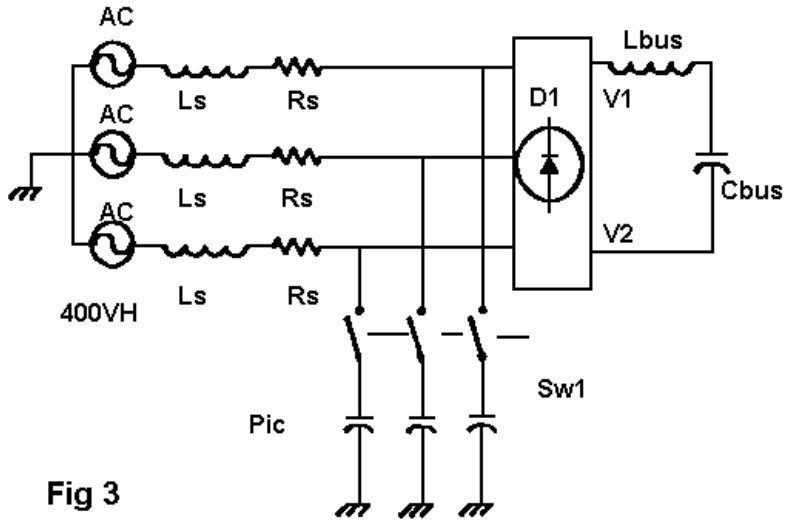

Fig 3

Lbus **-** Inverter DC link inductance (if present)
Cbus **-**inverter DC bulk capacitor**.**
D1 **-** Drive converter diodes / SCR's**.**

In the above circuit, if the transient which was described earlier is imposed between the V1 and V2 nodes the resultant current through the converter rectifier (D1) and Cbus can reach critical values**.** In simulation of the circuit of Fig**.** 3, the resultant voltage at V1**-**V2 and the current through Cbus is shown in Fig**.** 4**.**

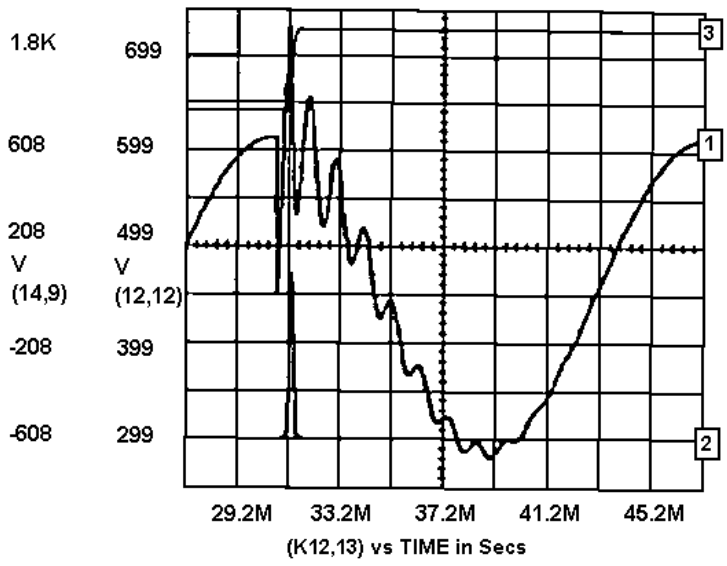

Fig 4

With respect to Figure 4:

- Waveform 1 is the line to line voltage transient due to the switching in of power factor correction capacitors with a peak value of approximately 1100V**.** The Volt*Seconds of the transient above the nominal is 0206 V*S**.**
- Waveform 2 is the current through the converter rectifiers and bus capacitor, The resultant current is 1400 amperes**.**
- Waveform 3 is the bus capacitor voltage value, nominally 650V but rises to 707V as a result of the current surge**.**

The primary issue, with respect to the currents observed in the drives structure, is their magnitude**.** Under less demanding conditions any transient impressed on the drive is “absorbed” in the DC link bus inductor, however if the energy contained in the voltage transient is greater than the volt*second capacity of the inductor, it will saturate**.** Under saturated conditions the di/dt limiting capacity of the inductor is greatly reduced, allowing the resultant current to reach explosive levels in a relatively short period of time**.**

Results / Effects - Nuisance tripping of VSI drives.

As is seen in Fig. 4, the DC bus capacitor voltage (waveform 3) rose from 640V nominal to 707V. This is a typical case and in many instances the bus voltage may rise to higher values (>800 volts for a 460V rated VSI drive) causing nuisance “over-voltage" trips.

Electrical component overstress.

- Fatigue of semiconductor rectifiers. Typical values with a 10HP 460V inverter drive for the converter rectifier diodes would be in the area of a 1200V device with a 50 ampere continuous dc output current rating. This type of diode has I_{fsm} (1/2 cycle surge current rating) of 500 amperes sinusoidal pulse, 10 milliseconds in duration and a 1^2 t rating of 1250 A^2 S. As can be seen by the waveforms of Fig. 4 the peak current of 1400 amperes is clearly overstressing the rectifier diode.

- Fatigue of line fusing. Typical high speed fuses, which are commonly used to protect VSI drives, will experience an aging phenomena when exposed to high current pulses of short duration. A fuse will operate normally without degradation if sized properly for a constant or predictable maximum load. If, however, the fuse is subjected repetitive high current overloads, the temperature in the fusible link will fluctuate causing two types of fatigue mechanical fatigue and thermal fatigue. Mechanical fatigue is precipitated by overloads of longer duration while the RMS current stays below the fuse current rating. The periodic heating and cooling of the fusible link will-weaken it and the mechanical stresses will eventually cause the link to open. Thermal fatigue is more likely the result when switched power factor correction capacitors are utilized. Higher temperatures in the fusible link caused by the short duration, high energy pulses will lead to grain growth within the molecular structure of the fusible link. This grain growth, which is permanent, weakens the element and will ultimately cause premature opening of the fuse and unnecessary equipment downtime. Either type of fatigue may reduce the nominal current rating of a fuse by 10 to 20%.

- MOV Over-voltage protection devices, typically Metal-Oxide Varistors (MOVs), can become stressed when subjected to non-destructive, high energy pulses. When these high energy pulses are applied to MOVs, heat will be produced within the device causing grain growth within the Zinc Oxide microstucture. This structure change will increase the leakage of the device which will lead to premature failure. Since MOVs usually fail “open", the circuit will be left without proper protection, leaving semiconductors susceptible to overvoltage failure.

Potential Solutions:

We start out with the premise that it is imperative that the implementation of power factor capacitors be “on demand" in accordance with the lagging Kvars present on the system at the time. Continuous application of power factor capacitors is not acceptable due to the leading Kvars the capacitors represent on a lightly loaded system. With this criteria, we will deal with some potential solutions to this transient problem and relative effectiveness of each proposed solution.

1). Incremental switching.

Add capacitors in steps to reduce the stored energy in the source inductance of the system. With this technique, capacitors are switched in via contacts at 10 - 25% increments, depending on the reactive load. Referencing back to the circuit of Fig. 1, the result of changing the 900uf capacitor to 100uf is shown in Fig. 5.

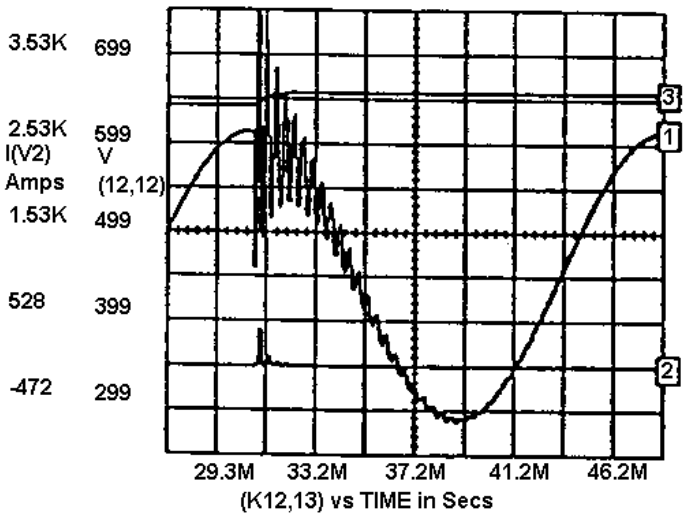

Fig 5

With respect to Figure 5:

- Waveform 1 is the line to line voltage transient due to the switching in of 10% of the power factor correction capacitors with a peak value of approximately 1100V**.** The Volt * Seconds of the transient above the nominal peak voltage is 0**.**077 V * S**.**
- Waveform 2 is the current through the converter rectifiers and bus capacitor**.** The resultant current is 395 amperes**.**
- Waveform 3 is the bus capacitor voltage value, nominally 650V but rises to 655V as a result of the current surge**.**

The significant changes due to switching 10°h of the total capacitance value is a net increase in the oscillation frequency and therefore a reduction in the positive volt-seconds applied to the VSI drive**.** This allows the VSl's DC link inductor to “absorb” the voltage transient, therefore reducing the peak current as compared to Fig**.** 4**.**

2). Zero voltage switching.

Since the energy stored in the source inductance is a result of the surge current into the capacitors (I = C dv/dt), if the caps are sequentially added to the line at the zero crossing of their respective line to neutral voltages, no current surge will be generated**.** This is the most effective means of eliminating the transients created by power factor capacitor switching, however this method is somewhat expensive since the capacitors would need to be actuated with an intelligent controller and a high current/voltage AC switch**.**

3).Precharge actuation.

If the capacitors are initially connected to the line through an appropriate buffer resistance, the initial surge current into the capacitors will be controlled by the chosen resistance, and after a “precharge” period the caps can be directly connected to the line**.** This method requires a careful examination of the resistance selected to minimize the phase shift between the line voltage and the capacitor voltage and therefore the resultant surge current**.** Parasitic inductance of the chosen resistance may also be a factor**.** The following is a simulation where the resistor is sized to equal approximately 1/3 of the capacitive reactance of the 900uf per phase load**.** (1 ohm)

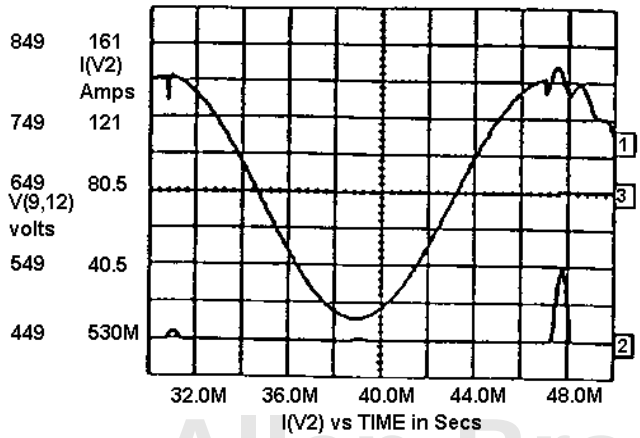

Fig 6

With respect to Figure 6:

- Waveform 1 is the line to line voltage transient due to the “precharging" of power factor correction capacitors with a peak value of approximately 715V**.** The Volt * Seconds of the transient above the nominal peak voltage is 0**.**038 V * S**.**
- Waveform 2 is the current through the converter rectifiers and bus capacitor**.** The resultant current is 40 amperes**.**
- Waveform 3 is the bus capacitor voltage value, nominally 650V and rises only to 655V as a result of the current surge**.**

The net resultant power in the resistor is a peak of 78KW with

an RMS wattage of 11KW for 16 milli-seconds. For reference the capacitor / resistor combination was switched in at 31ms and the series resistor switched out at 47ms, a delta of 16ms. Parasitic inductance of the limiting resistor does not appear to be critical because the resistor does provides adequate damping. This is a highly effective method of minimizing the transients due to switching PFC. The current magnitudes are easily controlled with a relatively low cost implementation with an appropriately chosen resistor, contactor and timer relay.

4). Buffer impedance:

Employment of a non-switched, capacitor (minimum value) can be very effective. Although it is undesirable to have leading Kvars in circuit under lightly loaded conditions, it may be advantageous to maintain a minimum value (10-20% of the total Kvars) on the line as an energy source for precharging the remainder of the Kvars on demand. If 20% (~200uf) is left permanently connected to the AC line and the remaining 700uf is switched. the results

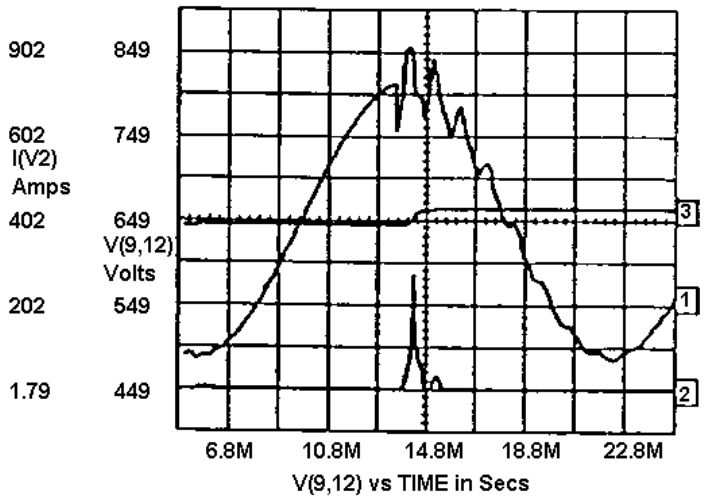

Fig 7

With respect to Figure 7:

- Waveform 1 is the line to line voltage transient due to the switching in of 80% of the power factor correction capacitors with 20% resident on the line. The peak value is approximately 816V with a transient The Volt * Second product of 0.048 V * S.
- Waveform 2 is the current through the converter rectifiers and bus capacitor. The resultant current is 255 amperes.
- Waveform 3 is the bus capacitor voltage value, nominally 650V but rises to 669V as a result of the current surge.

As can be seen this method has moderate surge current mitigation capacity but is very effectively implemented with just some minor wiring changes.

5).Energy Trap:

The use of poly phase reactors on the line side of the VSI drive can be very effective. If no additional precautions are taken, the use of a 3-5% reactor placed on the 3 phase input to the VSI will act as an “energy trap” to hold the surge voltage created from switching the power factor correction capacitors onto the line and bleed it back to the drives bulk capacitor in a more subtle fashion. The use of a 5% reactor is shown in the simulation of figure 8.

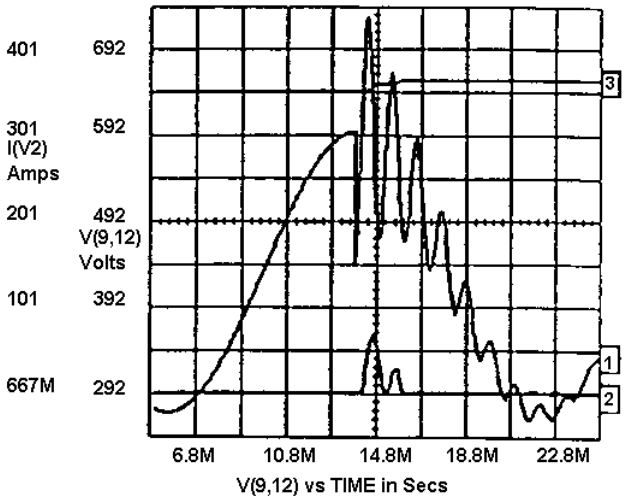

Fig 8

With respect to Figure 8:

- Waveform 1 is the line to line voltage transient due to the switching in of 100% of the power factor correction capacitors with a 5% 3 phase reactor in the drives line supply**.** The peak value is approximately 1180V with a transient Volt * Second product of 0203 V * S**.**
- Waveform 2 is the current through the converter rectifiers and bus capacitor**.** The resultant current is 68 amperes**.**
- Waveform 3 is the bus capacitor voltage value, nominally 650V but rises to 662V as a result of the current surge**.**

With the application of the 3 phase reactor in the drives supply, the transient voltage on the line due to cap switching is not affected, however the energy is “trapped” by the reactor and the net surge voltage seen at the drives input terminals is significantly reduced**.** This is the only proposed solution that protects the drive only and does little to protect the remainder of equipment which is connected to the distribution system**.**

Recommendations:

Given the 5 potential partial solutions described, the following table will attempt to summarize the characteristics of relative mitigation of distribution system transients due to the switching on line of power factor correction capacitors**.** Also the relative cost of installation / modification of an existing distribution system will be gauged**.**

Solution	V Peak	I Peak	Volt*Sec	$	Effectivity
None	1100	1400	0.201	0	0
1	1100	395	0.077	2	1
2	650	0	0	5	5
3	715	40	0.038	4	4
4	816	255	0.048	1	2
5	1180	68	0.203	3	3

None **-** present condition with random switched power factor correction caps**.**

1)**.** Incremental switching**.**
2)**.** Zero voltage switching
3)**.** Precharge actuation**.**
4)**.** Buffer impedance
5)**.** Energy trap**.**

In examining the above chart, the effectivety was gauged by the I Peak value generated in the VSI drive due to the switching of power factor correction capacitors**.** With respect to power distribution system, the figures of concern are the peak voltage value and its respective volt*second product Clearly the most effective solution is zero voltage switching of PFC capacitors, but this may not be feasible**.** In very practical terms it is possible to significantly reduce the stress put on all electrical I electronic equipment connected to an industrial power distribution system**.** Be it an existing system or a new installation, careful examination of the capacitor KVAR values and implementation using some form of precharge or buffer capacitance value will reduce overstresses on all equipment, providing longer years of trouble free service**.**

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