

REDUCING ELECTRICAL SYSTEM HARMONICS BY RELOCATION OF POWER FACTOR CORRECTION CAPACITORS

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Abstract: *The objective of the paper is to present the observations and findings of a methodology for reducing current and voltage harmonics by relocating the Power Factor Correction (PFC) capacitors already installed in a paper mill. The 415V medium voltage (MV) bus in the mill is supplied by a 11kV/433V, 1.6 MVA transformer and feeds induction motors, Variable Frequency Drives and lighting load. Power Factor was manually maintained almost at unity with plain capacitors at the panel. A previous study using Power Quality Analyser C.A 8332 revealed that the quantum of harmonics is more than the desirable limits. Subsequently, the present study was done using a low cost harmonic indicator and an Energy Management System. Harmonic data were recorded on a continuous basis for various product runs. This revealed that original harmonic current generated due to the VFDs in the network was only 14A. This was magnified to 136A for a specific product run when the load current was 1033A. In another product run it was magnified to 266A when the load current was 548A. Behavior of transformer, induction motors and plain capacitors in the network was studied at harmonic frequencies when these linear devices are in parallel with nonlinear loads. Magnification of harmonics took place due to the power factor correction (PFC) capacitors at the MV panel. By relocating 50% of the PFC capacitors nearer to the linear loads, the total harmonic current was reduced to 130A from the previous value of 266A. It was*

also observed that before relocation of the capacitors, many a times the PF was leading. After relocation, the PF was always near unity and lagging.

Key words: *Harmonics, power factor correction capacitors, resonance*

1. INTRODUCTION

Harmonics levels are increasing in power systems due to proliferation of non linear loads like rectifiers, variable frequency drives (VFD), uninterruptible power supplies (UPS), switched mode power supplies (SMPS) in appliances, arc and induction furnaces, fluorescent lamps with electronic ballasts, etc. [1]. Field surveys indicate that the harmonics are significant in many industries as reported in [2].

Harmonic resonance occurs in a power system when the power system's natural frequency corresponds to the frequency of a source of harmonic current [3]. Every power system has a natural frequency which is a function of the system reactance and the amount of power factor correction (PFC) capacitors connected to the system. In the event that there is a source of excitation with a frequency near or equal to the system's natural frequency, large resonant currents can result. The capacitors themselves are not a source of natural frequency excitation current, but can have the effect of magnifying such currents. It is common for power systems that

are corrected with capacitors to near unity power factor to have a natural frequency in the vicinity of 300Hz or 350Hz or the fifth or seventh harmonics. This magnification has implications in two aspects: reduced effective power factor and unreasonable indication of harmonic indices [4]. Harmonic magnification can be reduced by relocation of PFC capacitors.

2. ILL EFFECTS OF HARMONICS

Harmonics produce many ill effects such as: very high neutral currents in 3P-4W system, high neutral to ground voltages, over heating of neutral conductor, reduced power factor, failure of PFC capacitors, overloading of distribution transformers, distorted voltage waveforms to other loads, nuisance breaker-tripping, incorrect meter functioning, failure of protection relays, increased system losses as heat, etc.

3. STANDARD FOR LIMITS ON HARMONICS

IEEE Std. 519 - 1992 specifies the allowable limits for voltage and current distortion at various bus and system voltages. The IEEE Std. 519-1992 standard defines Total Harmonic Distortion in voltage (THD) and Total Demand Distortion in current (TDD) as below:

$$THD = \sqrt{\sum_{n=2}^{50} \left[\frac{V_n^2}{V_1^2} \right]} \quad (1)$$

where V_1 is the amplitude of fundamental voltage component and V_n are the amplitudes of the harmonics.

$$TDD = \sqrt{\sum_{n=2}^{50} \left[\frac{I_n^2}{I_1^2} \right]} \quad (2)$$

where I_1 is the amplitude of fundamental load current voltage component and I_n are the amplitudes of the harmonics.

In many literatures, THD_v is interchangeably used for THD and THD_i is interchangeably used for TDD. IEEE Std. 519 - 1992 specifies the allowable limits for voltage and current distortion at various bus and system voltages. Harmonics are measured at the Point of Common Coupling (PCC) which can be the primary or secondary of a utility transformer or at the service entrance of the supply or between the non-linear loads and other loads of an industrial plant. These are given in Table 1 and Table 2.

Table 1 Voltage Distortion Limits

Bus Voltage at PCC	THD (%)
≤ 69 kV	5.0
69.0001 kV - 161 kV	2.5
> 161.001 kV	1.5

Table 2 Current Distortion Limits For General Distribution Systems (120V through 69000V)

I_{sc} / I_L	TDD (%)
< 20	5.0
20-50	8.0
50- 100	12.0
100-1000	15.0
>1000	20.0

4. DESCRIPTION OF THE SYSTEM

This study was conducted in a paper mill which draws 11kV supply from the grid. A user owned transformer of 1.6 MVA, 11kV/433V rating supplies power to all the loads with 415V at 3 phase feeding induction motors, several VFDs (totaling 1757.5 hp) and 230V at single phase feeding production floor lighting, fans, air conditioners,

computers, other office equipment (totaling 12 kW). The total connected motor load in the process is thus 1772 hp. Each functional area is sectionalized so that the different operations can be run in tandem or in batches. The motors are at distance of approximately 80 meter from the MV panel room where initially all the PFC capacitors were kept in one place. The capacitor bank consisted of 400 KVAR (2 x 100 KVAR + 3 x 50KVAR + 2 x 25 KVAR). There are totally 78 induction motors with rating ranging from 0.38kW (0.5 hp) to 127.5kW (170 hp). The motors with a rating more than 10 kW are listed in Table 3.

Table 3 List of motors above 10kW rating

No.	Name of the motor	Rating (kW)
1	Hydro pulper	75.00
2	Tridisc refiner-1	112.50
3	Chest pump -1	22.50
4	Chest pump -2	15.00
5	Chest pump -3	15.00
6	Chest pump - 5	15.00
7	ATS pulper pump	11.25
8	Turbo -2	15.00
9	Tridisc refiner -2	112.50
10	Tridisc refiner-3	150.00
11	ATS Pulper	56.25
12	Turbo-1	18.75
13	Fan pump	45.00
14	Back water-3	15.00
15	High pressure screen-1	22.50
16	High pressure shower	11.25
17	Vacuum pump	75.00
18	MG Blower-1	11.25
19	Rewinder	18.75
20	ID fan	15.00
21	Main motor	127.50

Out of the above motors, fan pump, Rewinder, ID fan and main motor only are controlled by VFDs. All the others are supplied from the line through Star-Delta starter.

Salient details of the original network are shown in Figure 1. Power factor was maintained almost unity with plain capacitors at the MV panel, manually controlled to go with load. The industry was getting the incentive for good power factor from the State Electricity Board.

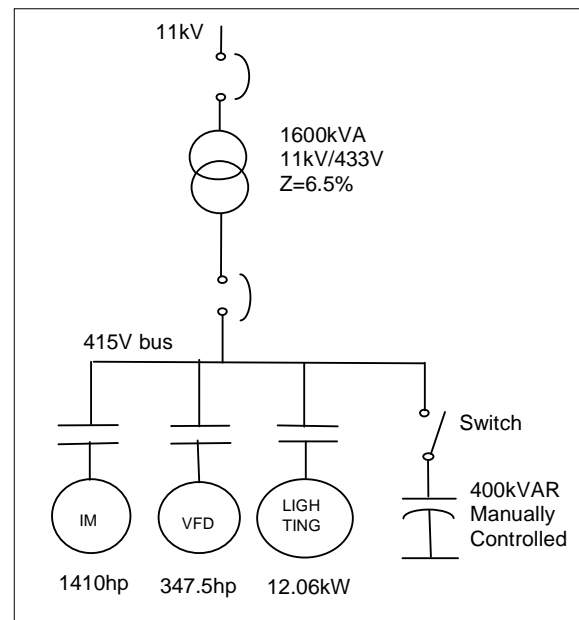


Fig. 1. Single Line Diagram of the original network

Since the VFDs are present in the network, a harmonic study was conducted using a Power Quality Analyser CA8332. It was observed that the current harmonics were higher than 5% as prescribed in the IEEE 519 standard. The values of current harmonics recorded at the PCC (415V bus) are given in Figure 2. The THDi in R phase load current was 12.9%; in Y phase it was 13.1% and in B phase it was 12.1%.

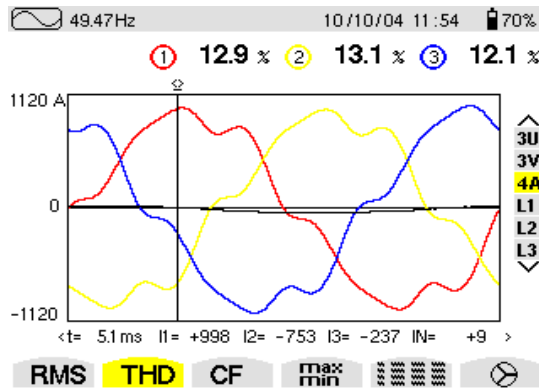


Fig. 2 THD_i measured at the 415V bus (PCC) of the MV Panel.



Fig. 3 Harmonic Indicator

5. LOW COST HARMONIC INDICATOR AND EMS

5.1 Harmonic Indicator

Since different product runs call for different connected load, it was decided to perform a detailed harmonics and power flow study for long durations (rather than for small intervals). Hence a low cost harmonic indicator to measure up to 15th harmonics, developed by a Company in Chennai, was used. Voltage / current harmonics, RMS values of voltage / current, fundamental value of voltage / current can be continuously monitored and communicated with a 485 port. An Energy Management System (EMS) software developed by the same Company was installed in a Personal Computer (PC).

The harmonic indicator displaying THD in voltage is shown in Figure 3. This approach has two advantages:

- 1) low cost and
- 2) the large storage capacity of the PC facilitates recording the various parameters continuously for long duration.

(Having realized the advantages, the plant has permanently installed the total system for continuous studies and improvement).

5.2 The Data Acquisition System – EMS

The EMS has the following facilities needed for "Demand Side Management". The system comprises of power measurement products (comprising of Energy Meters, Multifunction Meters, Load Managers and Trivector Meters), interface products, data converters, communication cables and software package. The Interface Products consist of a data logger required for interfacing pulse output type energy meters. Each data logger has a provision to connect 16 / 32 meters. The Data Concentrator is used for interfacing meters with RS485 output. Each data concentrator can support 32 individual meters.

The graphical representation has Mimic View, Online Data View in tree structure, Single Line Diagram, Bar Graphs and Trends. It can generate alarms, events and reports. Sample data of power parameters is shown in Table 4.

Table 4 Display of Power Parameters

Time	KVA	KW	KVAr	PF
14:00	504	504	5	-1
4:10	456	453	50	-0.99
14:20	531	531	22	0.999
14:30	513	513	3	1
14:40	515	514	12	1
14:50	526	526	10	1
15:00	559	558	43	0.997
5:10	549	548	30	0.999
15:20	543	543	25	0.999
15:30	538	537	27	0.999
...

Data collected for about a week in EMS for various product runs revealed that original harmonic currents generated due to the VFDs in the network was only 14A for a load current of 109 A with a voltage harmonic of 1.8% . This was magnified to 136A for a specific product run when the load current was around 1033 A with the voltage harmonic of 4.2%. In another product run it was magnified to 266A when the load current was 548A with a voltage harmonic of 6.4%. All the above initial study is shown in Table 5 retrieved from EMS.

Table 5 Readings of initial study

	Date	Time	Readings
1	7.12.07	02.00hrs	$I_L = 1033A$ $I_{har} = 136A$ $V_{THD} = 4.2\%$
2	16.1.08	04.36hrs	$I_L = 548A$ $I_{har} = 266A$ $V_{THD} = 6.4\%$
3	17.1.08	09.34hrs	$I_L = 109A$ $I_{har} = 14A$ $V_{THD} = 1.8\%$

6. ANALYSIS

Behavior of Transformer, Induction motors and plain capacitors in the network was studied for harmonic frequencies by calculating bus impedance when these linear devices are in parallel with harmonic generator. A mathematical model was developed for ease of calculation for this purpose. The calculated bus impedances and consequent harmonic currents / voltages in these linear devices were compared with the actual measurement of harmonics from the EMS. With these data, it was possible to predict the harmonic performance for different transformer rating, load conditions and different PFC capacitors.

Also it was possible to design a suitable filter to mitigate the harmonics from the original generated level. The effect of network components is explained as under for the harmonic frequencies.

6.1 Effect of Transformer in the network:

Net harmonic current flowing through the transformer = that originally generated by nonlinear devices + that magnified by PFC capacitors – that mitigated by inductive load and filters. Transformer of higher rating with lower percentage impedance reduces the bus impedance for harmonic frequencies and hence reduces net harmonic current flow in the transformer.

6.2. Effect of Induction motors in the network:

Induction motors decrease the net bus impedance for harmonic frequencies and hence net harmonic current flow in the transformer is less. Also the harmonic current flowing through the induction motors mitigates the original generated harmonic.

6.3. Effect of PFC capacitor in the network:

PFC capacitors increase the bus impedance for harmonic frequencies and even a slight voltage harmonic (developed due to the original harmonic current) causes a large harmonic current in the PFC capacitors as their impedance falls drastically with frequency. And these currents are flowing through the transformer in addition to the original harmonic current causing magnification. Additional such currents increase the voltage harmonic further at the bus and further flow of currents in PFC capacitors result in a cascading effect until an equilibrium is reached. In other words, original generated harmonic currents are magnified several times when it is flowing through the transformer.

Harmonic currents are generated at load end by non linear loads and flow through different bus sections and finally through the secondary windings of the transformer. Hence, the harmonic voltage drop is near zero at the load end and maximum at transformer end. This harmonic voltage circulates the harmonic current through the PFC capacitors when connected. It is logical to conclude the circulating harmonic current will be at maximum at transformer end and less at load end. The case is worse, if the distance from the transformer and load is more.

With the understanding of the behavior of all linear loads for harmonic frequencies, it can be observed that no PFC capacitors should be allowed to make net impedance capacitive at harmonic frequencies. An inductive reactor if connected in series with the capacitor, make net bus impedance inductive to have absolute nil magnification of originally generated harmonics. In such case the series resonant frequency should be much less than the harmonic frequency present in the system, a phenomenon called “detuning”.

As analyzed above major magnification of the originally generated harmonics was not permitted to happen. In fact if PFC capacitors are avoided either at transformer end or at motor end and only series reactors to bus connected capacitors are employed, a certain amount of mitigation of originally generated harmonics would take place. In this study there was no parallel resonance of PFC capacitors with transformer impedance, only rise in bus impedance causing magnification.

7. RELOCATION OF CAPACITORS

In the case study taken, first 50% of the total capacitors connected to the MV panel bus were removed and distributed across the motor terminals as shown in Figure 4 so as to have less harmonic voltage rise. With this, for the product run where the total harmonic current was 266A is now reduced to 130A. Also voltage harmonic is reduced from 6.4% to 3.8% at transformer end as given in Table 6. It can be observed that the mitigation of harmonics is effected almost with zero investment.

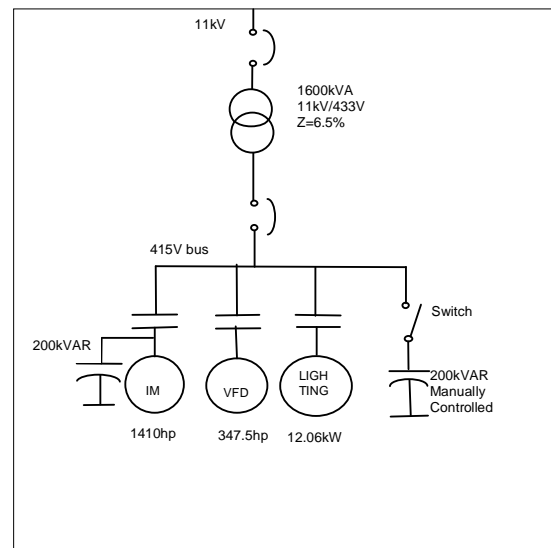


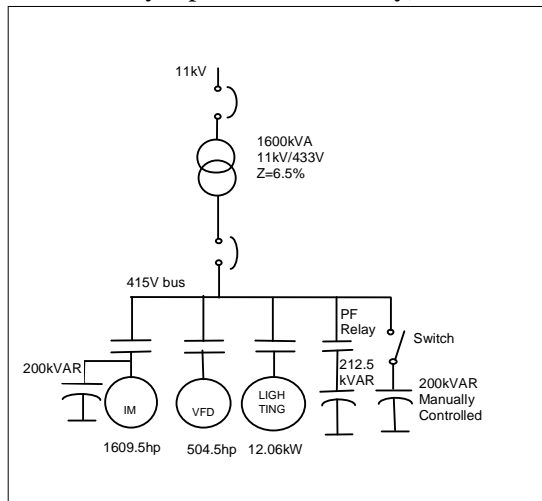
Fig. 4

Table 6

	Date	Time	Readings
1	29.7.08	15.30hrs	$I_L = 928A$ $I_{har} = 117A$ $V_{THD} = 3.1\%$
2	29.12.08	13.00hrs	$I_L = 534A$ $I_{har} = 130A$ $V_{THD} = 3.8\%$

Now, the balance 50% of the manually controlled capacitor 200 KVAR is replaced by an automatic PF control panel of 212.5 KVAR rating. This prevents any possible leading PF.

At this stage the plant wanted to add around 350 hp including a non-linear load of around 155 hp with an additional PFC of 200 KVAR at the MV bus – distribution of the network shown in Figure 5. Now the 1.6 MVA transformer sees a total PFC capacitors of 612.5 KVAR (200 KVAR at motor terminals + 200 KVAR fixed at the MV panel + 212.5 KVAR again at the MV panel controlled by a power factor relay).

**Fig. 5**

Now the harmonic current went up to around 252A for a load current of 897A with voltage harmonic as high as 6.8% as shown in Table 7. This is mainly due to the addition of

200 KVAR capacitor which causes major magnification.

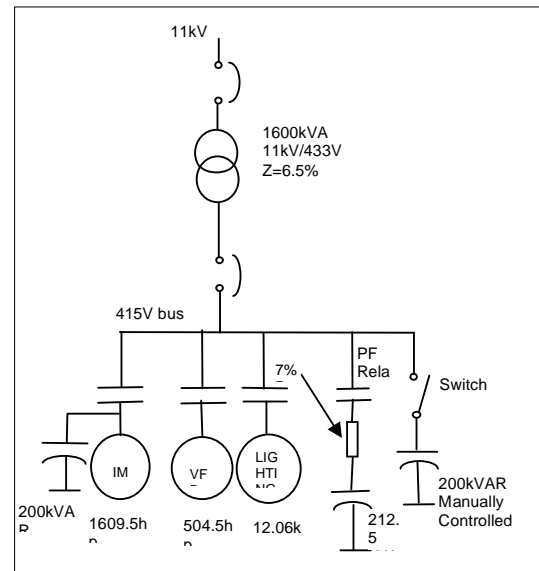
Table 7

	Date	Time	Readings
1	8.6.09	21.15 hrs	$I_L = 897A$ $I_{har} = 252A$ $V_{THD} = 6.8\%$

Since the above harmonic condition was not acceptable, at this stage 7% reactors were introduced to 212.5 KVAR capacitors at the MV panel with the power factor relay. The network and the improvement in the harmonic performance i.e. the mitigation are shown in Figure 6 and Table 8. Harmonic current now is 125A and voltage harmonic is 3.2% for a load current of 1132A. Here again it can be seen, a reduction of harmonic current to the extent of 127A is achieved at a very nominal investment.

Table 8

No.	Date	Time	Readings
1	27.7.09	16.15hrs	$I_L = 1132A$ $I_{har} = 125A$ $V_{THD} = 3.2\%$

**Fig. 6**

Calculation of power loss in the transformer secondary windings due to the fundamental and harmonic currents was made for the actual values with a mathematical model and the same calculated loss was validated to some extent by actual measured data from the EMS package.

Now the harmonic current is around 11% of the load current with reduced magnification. This warrants further action. The remaining 200 KVAR at the transformer end is to be either shifted to near load at MCC panels or 7% reactors are to be introduced to it and controlled through a PF relay so that the originally generated harmonic current will see nil magnification and also see mitigation. With this set up the harmonic current is expected to be less than the originally generated value of around 20A, for the expanded load. It then will be less than the recommended value of 5% of the load current.

7.1. Comparison voltage and current harmonics before and after relocation of capacitors

Table 9. Voltage and current harmonics before relocation of PFC

	Voltage (V)	Current A
THD	3.9 %	25.5 %
Fundamental	237.2 V	644.4 A
Order of harmonics	Percentage of harmonics	
2	0.0	0.0
3	0.1	0.7
4	0.0	0.0
5	3.3	21.9
6	0.0	0.0
7	2.9	12.9
8	0.0	0.0
9	0.1	0.5
10	0.0	0.0
11	0.6	2.0
12	0.0	0.0
13	0.2	0.5

14	0.0	0.0
15	0.0	0.0

Table 10 Voltage and current harmonics after relocation of PFC

	Voltage V	Current A
THD	3.0 %	17.9 %
Fundamental	244.4	669.4
Order of harmonics	Percentage of harmonics	
2	0.0	0.1
3	0.2	2.2
4	0.0	0.0
5	1.7	14.3
6	0.0	0.1
7	1.7	8.5
8	0.0	0.0
9	0.1	0.7
10	0.0	0.0
11	1.9	6.3
12	0.0	0.0
13	0.5	1.5
14	0.0	0.0
15	0.0	0.1

The reduction in voltage and current harmonics after relocation of PFC are shown in Figure 7 and Figure 8 respectively.

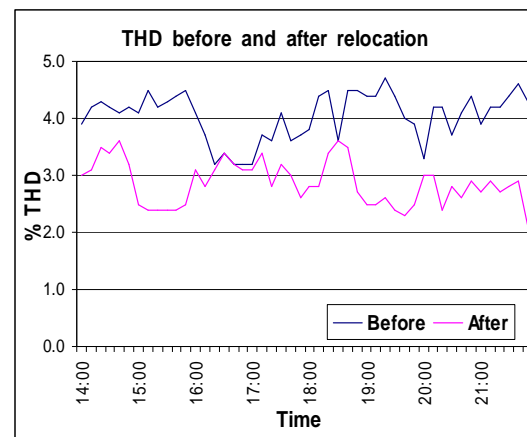


Fig. 7 Reduction in voltage harmonics measured for a duration of 8 hours

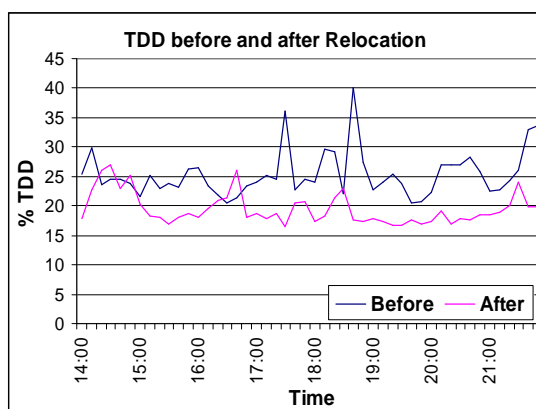


Fig. 8 Reduction in current harmonics measured for a duration of 8 hours

9. CONCLUSION

For the compensation of the inductive load in the industry, PFC capacitor is the cost effective solution. Even though the originally generated harmonics due to non-linear load is less than harmful level, wrong location of PFC capacitors multiply the harmonics to a very unacceptable level. At times, it is inevitable that the PFC capacitor has to be at the transformer end. Hence i) locating the part of PFC capacitor nearer to the load to minimize the magnification and ii) also making the PFC capacitor at transformer end inductive at harmonic frequencies with series inductor controlled through PF relay are likely to be the cost effective approaches to see the harmonic level within very acceptable level.

REFERENCES

- 1) J.Arrillaga, D.A.Bradley, P.S.Bodger, "Power System Harmonics", John Wiley & Sons, 1985.
- 2) K.R.Valluvan, A.S.Kandasamy and A.M.Natarajan, "A Survey of Voltage and Current Harmonics in Various Industries Connected to a State Electrical Grid", Intl.

J. of Applied Engineering Research, ISSN 0973- 4562, Volume 3, Number 6, 2008.

- 3) Francis M. Fernandez, P. S.Chandramohan Nair, "Influence of Power Factor Compensating Capacitors on Estimation of Harmonic Distortion", 9th Int. conference on Electrical Power quality and Utilisation, Barcelona, 2007.
- 4) Mark Mcgranaghan Scott Peele and Dan Murray, "Solving Harmonic Resonance Problems On The Medium Voltage System", CIRED, 19th International Conference on Electricity Distribution, Vienna, 21-24 May 2007.

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