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A literature survey on power quality disturbances in the frequency range of 2-150 kHz

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Abstract. *Modern power electronics emit high frequency disturbances which are the remnants of their internal switching circuits. The electromagnetic interference, induced by these high frequency disturbances, can cause household equipment and utility assets to malfunction. Due to the lack of standardization in the frequency range of 2-150 kHz, power electronic devices have been designed to satisfy emission limits at lower frequencies but instead have increased emission at this higher frequency range. This paper presents an up-to-date literature survey on these high frequency disturbances in the 2-150 kHz range, a.k.a. 'supraharmonics'. It includes classification, standardization, equipment interaction, propagation, and mitigation methods. This survey shows that most research conducted on this topic has been empirical or using simple models. However, analytical/physical models with sufficient detail have to be developed for equipment and low-voltage networks in this frequency range to increase understanding of the practical impact on end-user equipment and assets in the distribution grid. Supraharmonics are a relatively new power quality problem and this emission is expected to increase progressively due to the growing number of high frequency emitting devices, and the increasing number of susceptible loads. Hence, more research towards higher frequency harmonics is warranted.*

Key words

Electromagnetic Interference, Power Electronics, Semiconductor Switches, Supraharmonics.

I. Introduction

In the early days of power electronics, diodes and thyristors were the main components in switching circuits. These line commutation based semiconductor switches generate very low order harmonics. However, modern self-commutating switches (e.g. transistors) can generate harmonics with decisively higher frequencies [1]. Common and widespread, high frequency emitting, power electronic applications are e.g. active power factor correction to reduce lower order harmonics, pulse width modulation to regulate power output and for power conversion, or switch mode power supplies to improve energy efficiency.

The amplitude of power electronic high frequency emission is generally very small, often in the range of milliamperes [2-4] (see e.g. insert *Fig. 4*). However, the number of reports ascribing equipment malfunction due to electromagnetic interference (EMI), which is induced by these high frequency disturbances, is currently growing and expected to increase progressively due to the growing number of high frequency emitting sources, and the increasing number of susceptible loads [5]. Some examples of reported EMI are the disruption of traffic lights and digital clocks, erroneous smart meter read-outs, or compromised power line communication (PLC).

Research into high frequency emission and its subsequent EMI is still premature. However, the research on this relatively novel power quality problem is steadily growing. This paper presents a literature survey on these high frequency power quality disturbances in the frequency range of 2-150 kHz. This survey is based on articles published mainly in the period 2009-2016. Section II provides definitions and denotes the different classes of emission. An overview of prominent standardization work is presented in section III. Sections IV and V provide information on equipment interaction, and the propagation of the high frequency emission, respectively. A brief overview of mitigation approaches is given in section VI, and finally, in section VII, the main findings and conclusions from this literature survey are summarized.

II. Definition and Classification

Voltage and current disturbances in the frequency range of 2-150 kHz have been referred to as 'supraharmonics' [6]. The term 'supraharmonics' is relatively novel and it is still a point of discussion mainly because the term is used to describe all waveform disturbances in the 2-150 kHz range, including time-varying and transient signals which violate the standard definition of (inter)harmonics. Nonetheless, the term 'supraharmonics' is gaining traction and it will be used throughout this paper.

Supraharmonics have been classified into 3 categories [7]

1. Narrowband signals, i.e. disturbances that roughly appear as individual frequencies, having a bandwidth < 5 kHz [8]. This type of disturbance is induced by e.g. PLC, fluorescent lights with high frequency ballasts, or induction cookers.

2. Broadband signals, this type of signal is often emitted by end-user equipment with active power factor correction. Moreover, this signal can be defined to have a bandwidth > 5 kHz.
3. Recurrent oscillations, i.e. transient current distortions that occur in the vicinity of the voltage zero-crossing in single phase power factor corrected ac-dc converters [9]. This phenomena occurs every ½ cycle of the fundamental frequency (i.e. every 10 ms for a 50 Hz system).

Arguably a more comprehensive classification of these high frequency waveform disturbances can be defined based on the temporal characteristics of the disturbance signal, i.e. (A) transient signal, (B) time-invariant periodic signal and an intermediate category between A and B, i.e. (C) a time-varying signal.

III. Standardization

Standards for (inter)harmonics up to 2 kHz, have been formalized in e.g. EN 50160, IEEE Std. 519, and IEC/CENELEC electromagnetic compatibility (EMC) standards [1]. The frequency range below 2 kHz is well covered by standards as mitigation of these lower harmonics is required for reliable power systems operations [7]. Above 150 kHz, electromagnetic radiation starts to play a role. Hence, strict emission limits above 150 kHz have been imposed by the broadcast community through e.g. the CISPR standards. Subsequently, a standardization gap existed for the frequency range of 2-150 kHz. As a consequence, electronic products have been designed that satisfy harmonic emission limits at lower frequencies (< 2 kHz) but instead have increased emission in the frequency range of 2-150 kHz [10]. As the number of reported complaints increase, efforts are redirected by standardization bodies to develop compatibility, emission, and immunity levels for this frequency range of 2-150 kHz. Prominent working groups and technical committees (TC) that touch upon the topic of supraharmonics are denoted below.

TC 77 is founded by the International Electrotechnical Commission (IEC), and is assigned to prepare standards regarding EMC [11]. It covers emission standards and deals with immunity related items. Although, product immunity standards are not provided, but left to be specified by specific product committees. The IEC/TS 62749 specifies the expected characteristics electricity at the supply terminals of public grid, and thereby provide recommendations regarding different classes of power quality disturbances [12]. Within the standardization body CENELEC, the TC 8X and TC 210 have been founded to gather information on reported cases of observed EMI due to supraharmonic emissions [13]. The resurgence of interest for PLC has been noted as the main driving force regarding the founding of the CENELEC TCs [5]. CENELECS's SC205A produced a study report on EMI between electrical equipment and power systems in the frequency range below 150 kHz. In this report the main equipment categories of emission sources were identified to be lighting equipment, inverters, rectifiers, and power supplies. CIGRE's C4/C6.29 [14], TB672 "Power-quality aspects of solar power", C4.31: "EMC between Communication Circuits and Power Systems" includes recommendations regarding PLC, and C4.24, "power quality in the future grid", investigates in which way the power quality is expected to change in the future grid in part due to the energy transition [15]. The IEEE project P1250, provides guidelines to assist power system designers and operators to delivering power quality that is compatible with electrical end-use equipment, where supraharmonics are part of TC 7 of the IEEE EMC society [16]. In the following sections, European and international standards that cover the supraharmonic frequency range with respect to emission, immunity and compatibility will be given.

A. Emission limits and measurement standards

Maximum limits on broadband emission are defined in the European standard EN 50065 [8] and in two broadcast standards, i.e. the CISPR 11 and 15. The former CISPR standard sets mandatory limits on emission from high performance scientific, medical or industrial equipment. The latter CISPR standard sets the same emission limits, but then provisional, for electrical lighting equipment; a very common source of broadband supraharmonic disturbances [7]. IEC TS 62578 describes the operation conditions and typical characteristics of active infeed converters. This technical specification includes recommended maximum (non-intentional) emission values for converters in the 2-150 kHz. The emission limits of the aforementioned standards are shown in *Fig. 1*. Generally, broad band emission limits decrease as the frequency increases; this is to accommodate PLC.

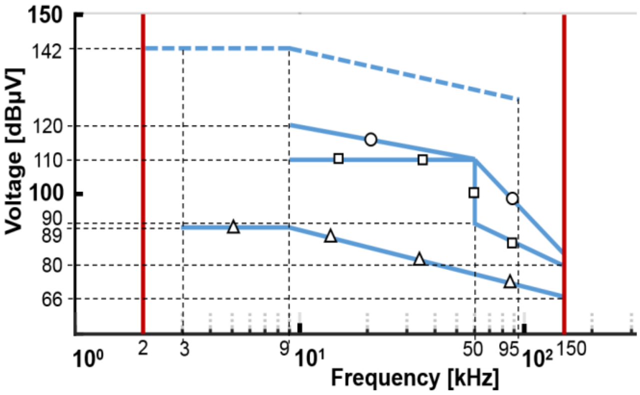

Fig. 1 Broad band emission limits according to IEC TS 62578 (○), CISPR 15 (□), and EN 50065 (△). Narrow band limits from EN 50160 (dashed line) are given as a reference.

A renewed interest has emerged for PLC due to the roll-out of smart-meters and so called smart-grid applications [17]. PLC is a source of intentional, (mainly) narrowband emission in the range of 3-148.5 kHz . Emission standards for narrow band signals are given in EN 50065-1 and IEC 61000-3-8 [18]. The emission limits of these two standards coincide for the frequency range of 3-148,5 kHz. EN 50561-1 focusses primarily on PLC emission for frequencies >150 kHz [19]. The PLC signal power is dynamically reduced as frequency increases in order to minimize the probability of radio disturbance [18]. Limits for intentional signalling emission are also given in EN 50160 [20].

The emission limits of these narrowband standards are shown in *Fig. 2*.

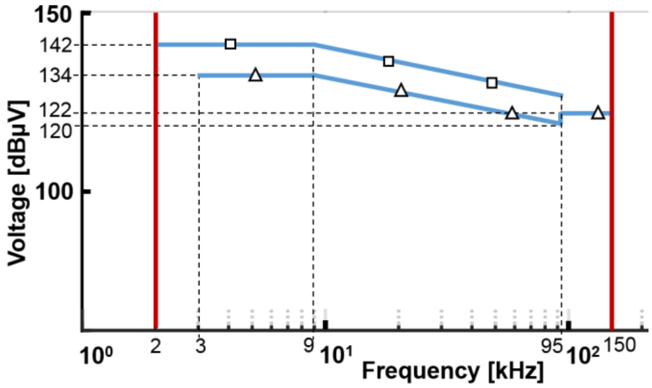

Fig. 2 Narrow band emission limits according to EN 50160 (□), aand IEC 61000-3-8 (△).

Currently, no specific standards exist regarding recurrent oscillations. This is potentially due to the lack of accurate knowledge on voltage levels and frequencies that occur in low voltage installations [7]. However, significant voltage disturbances in the order of volts have been observed and ascribed to the recurrent oscillation phenomena [21].

In order to establish emission limits and compatibility levels, reliable and reproducible measurement methods are required. Currently, three standards exist that describe measuring methods applicable to the 2-150 kHz frequency, i.e. IEC 61000-4-7 [22], IEC 61000-4-30 [23], and CISPR 16-2-1 [24]. The latter is a radio broadcasting standard and it covers conducted disturbances in the range of 9 kHz – 30 MHz. This method involves the tuning of a narrow band receiver to measure the peak value of a desired single band frequency. Due to the time-frequency dependent nature of unintentional supraharmonic emission, this is a less suitable method compared to the IEC measuring standards. IEC 61000-4-7 covers the range of 2-9 kHz. In this standard, a discrete Fourier transform is used to convert the voltage time-series measurement to the time-frequency domain via rectangular time-windows with a length of 200 ms, and subsequently, the spectral lines are aggregated into 200 Hz bands. The IEC 61000-4-30 covers the frequency range of 9-150 kHz. This standard prescribes a high-pass filter to damp the fundamental voltage and lower order harmonics, and subsequently sample voltage time-series measurements of 200 ms with a frequency rate of 1024 kHz. Thus, 2 different IEC standards exist to cover the full range of 2-150 kHz. However, IEC 61000-4-7 has been used in measurement studies to cover the full supraharmonic range [7, 25, 26]. In [27], an in-depth comparison was performed between the two IEC measuring methods.

In the field of power systems, standards regarding harmonic distortions are traditionally based on voltage measurements. This is also true for the IEC measurement standards described above. However, a complication of measuring the voltage, instead of the current as is more common in the EMC field, is that the measurements are only truly comparable and reproducible if the grid impedance is also specified. However, the grid impedance is not specified in these measurement standards. Moreover, a fixed grid impedance value, as in e.g. a lab environment may not be representable for the real-life grid impedance which is expected to be highly time-varying in the LV network. Hence, in order to exchange and interpret e.g. research data or data to support standardization discussions, this shortcoming in the measurement standards needs to be resolved by specifying preconditions of the grid during measurements.

B. Immunity standards

The supraharmonic frequency range partially overlaps with the frequency range of transients, i.e. from several kHz up to 5 MHz [28]. Transient immunity testing procedures are described in IEC61000-4-4 [29] and IEC61000-4-5 [30]. However, the signal amplitude and energy content of transients are generally much larger than for supraharmonics [31]. Therefore, dedicated standards regarding immunity testing specifically in the supraharmonic frequency range have been defined. Two standards that describe testing techniques to demonstrate immunity against conducted disturbances in the frequency range of 2-150 kHz at AC power ports are IEC61000-4-16 [32] and IEC61000-4-19 [33]. The latter is specific to differential mode disturbances while the former deals with common mode disturbances. Differential mode disturbances originate generally from power electronics and PLC, while common mode disturbances are often induced by power line currents and return leakage currents in grounding systems [34]. The immunity testing methods prescribed in these standards are for voltages of all apparatus and also for current of metering devices. The voltage and current levels are to be determined by product committees.

C. Compatibility standards

Compatibility levels (i.e. reference levels in a specified environment for the coordination of emission and immunity limits to ensure that devices function properly with a high probability at the specified voltage level) have been proposed for PLC up to 9 kHz in IEC 61000-2-2. However, this standard is being extended to cover the full PLC range, i.e. up to 148.5 kHz by the TC77; where the lower range of the spectrum (2-30 kHz) will be allowed to carry more (broad band) disturbances from power electronics, and the upper range of the spectrum (30-148.5 kHz) will be reserved as a clean frequency band for PLC [34].
Compatibility standards for other applications than PLC are still lacking. This can partially be attributed to the fact that a comprehensive overview of emission spectra of different devices is still lacking. Moreover, the same type of device but from different manufacturers can have noticeably different emission spectra, and (harmonic) conditions in the grid influence the emission by devices. To further complicate the matter, the measured spectrum of a device can be significantly influenced by the presence of other devices connected to the same installation as will be explained further in section III. Due to the aforementioned factors, it is complex to make generalizations regarding emission spectra for classes of devices, and thereby hamper the development of standards.

IV. Equipment interaction

For traditional lower order harmonics, the phase angles of the harmonic distortion of devices within an installation tend to be more coherent [35]. Hence, a larger aggregated total amplitude of harmonic distortion is generally seen at the PoC as the number of harmonic emitting devices increase. For supraharmonics, on the contrary, the total emission from an installation at the PoC decreases as the number of supraharmonic emitting sources increases, while simultaneously, the current measured at the terminals of each individual device increases. To explain this about supraharmonics, a distinction is made between primary emission and secondary emission [36]:

- Primary emission is the part of the current that is driven by the internal emission of the device itself. Three factors affect this emission, i.e. the electronic topology of the device; the impedance at the local connection point, and the presence of resonances.
- Secondary emission is the part of the current that is driven by the internal emission from other devices or that originates from elsewhere in the grid. It depends on the relation between the grid impedance and the impedance at the device terminal.

The total current emission at the terminal of a device is the sum of these two components. In [37], a simple model has been used to investigate total current emission at the terminal of a device. This model is shown in *Fig. 3*, where N is the number of devices connected to the installation, $\bar{I}_{Di}$ is the internal current emission of a device, C is the capacitance of the EMC filter which is connected between the device and the grid, and R represents the grid impedance.

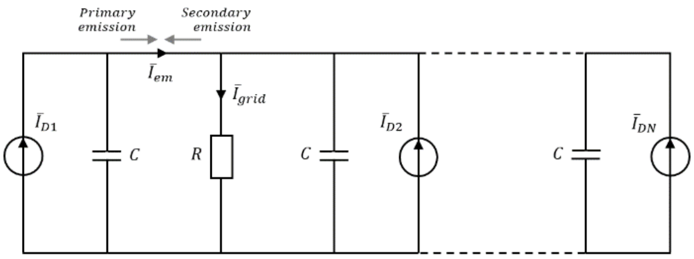

Fig. 3 Simplified model of *N* devices connected to the grid.

Via this model, a mathematical description of the total current emission at the terminal of a device, $\bar{I}_{em}$, was derived, see *Fig. 3* and equation (1), where $\alpha=\omega RC$, and ω is the frequency.

$$\bar{I}_{em} = \frac{1+(N-1)j\alpha}{1+Nj\alpha}\bar{I}_{D1} + \frac{j\alpha}{1+Nj\alpha}\sum_{i=2}^{N}\bar{I}_{Di} \qquad (1)$$

The amplitude of the current at the terminal interface of the device, assuming that the connected devices have an internal emission of the same amplitude I_n but of slightly different frequency, is given in equation (2).

$$I_{em} = \sqrt{\frac{1+N(N-1)\alpha^2}{1+N^2\alpha^2}}I_n \qquad (2)$$

From equation (2) it can be deduced that the emission measured at the terminal of a device is dominated by its own internal emission and is relatively independent of the number of connected devices, the switching frequency, capacitor size and the grid impedance.

The total emission from an installation that flows towards the grid, $\bar{I}_{grid}$, (see *Fig. 3*) is given in equation (3).

$$\bar{I}_{grid} = \frac{1}{1+Nj\alpha}\sum_{i=1}^{N}\bar{I}_{Di} \qquad (3)$$

The amplitude of this current, assuming that the connected devices have an internal emission of the same amplitude I_n but of slightly different frequency, is

$$I_{grid} = \frac{\sqrt{N}}{\sqrt{1+N^2\alpha^2}}I_n \qquad (4)$$

From equation (4) it is deduced that the emission of the total installation is inversely proportional to the square-root of the number of devices. Although, these equations have been derived from a very simple model, measurements have confirmed that peaks in the current spectrum reduce in an inversely square root trend when multiple devices are connected to an installation [4, 37]. To explain the reduction of the emission's spectral amplitudes at the PoC when the number of devices increase, it has been suggested that the emissions partially cancel each other out at the PoC due to phase angle dispersion of individual supraharmonics [35] and thereby homogenize and flatten the spectrum [38]. However, in other studies it has been indicated that the reduction of supraharmonic emission at the PoC is due to the low impedance path within the installation induced by EMC filters [36].

V. Propagation

An EMC filter is placed at the grid-side of the power electronic switching device to mitigate the supraharmonic ripple that is injected into the network [37]. The capacitors in the filter induce a low-impedance path within an installation. Therefore, in this kHz frequency range, the emission from devices will flow for a significant part between neighbouring power electronic equipment and thereby remain within the installation [36]. Within an installation, the high frequency current produced by a large device, can potentially cause a relatively high secondary emission to flow through a nearby small device and compromise it or its filter [39]. However, a device that emits larger supraharmonic currents will generally have a larger capacitor in its EMC filter and therefore is likely to receive secondary emission from smaller devices elsewhere in the network. Measurements in [36] show that the spectra of a smaller device (i.e. LED lamp) is rendered relatively unaffected by the presence of a larger device (i.e. electric vehicle), while the spectra of the large device was altered by the presence of the LED lamp.

The fraction of supraharmonics that propagate towards the public grid is expected to be relatively small, as the grid impedance is noted to be high at this frequency range [37], and the input impedance at the supply side of the PoC, is relatively low at higher frequencies due to the presence of EMC-filters. For lower parts of the frequency spectrum, the grid impedance measured at the PoC is greatly determined by cable and transformer inductances. However, more research is still needed to investigate the grid impedance at higher frequencies [40]. Voltage measurements in the frequency range of 2-150 kHz at the PoC have shown voltage distortion for a residential setting from about 0.4 V at 2 kHz, 0.1 V at 4 kHz, and 0.05 V at 10 kHz [41]. *Fig. 4* shows a simplified schematic of supraharmonic propagation, showing primary and secondary emission. It shows, as mentioned above, that a part of the supraharmonic emission propagates between devices, and another part towards the PoC.

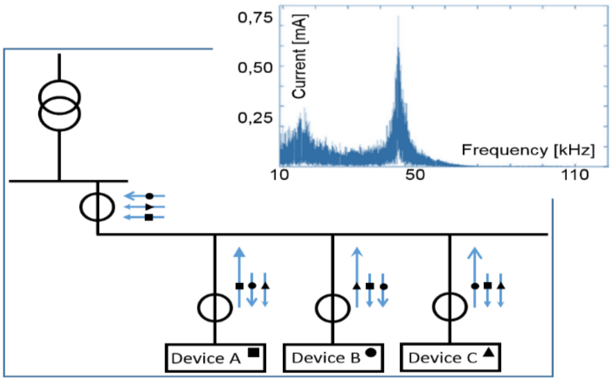

Fig. 4 A schematic diagram of supraharmonic propagation showing primary (large arrows) and secondary (small arrows) emission [36]. The insert (top right) illustrates the emission spectra of a LED lamp, a common soucre of supraharnonics.

When a large number of power electronic devices are connected to the same installation, the high frequency emission towards the grid may induce harmonic resonances, due to the capacitance in the EMC filters of the devices and the leakage inductance of transformers or inductance inherent to the feeders. In [39], the harmonic resonances have been investigated via a similar model as shown in *Fig. 3*, except that the grid impedance was extended with an inductor L in series. From this model, it was derived that for N devices the resonance frequency occurs close to

$$\omega = \frac{1}{\sqrt{NLC}} \tag{5}$$

and that the maximum high frequency current emitted from N devices to the grid is

$$I_{grid}^{max} = \sqrt{\frac{L}{C}}\frac{\sqrt{N}}{R} I_n \tag{6}$$

Equations (5) and (6) indicate that resonance frequency decreases proportionally with the square root of the number of devices and the current amplification increases with the same value. Hence, due to resonances, the supraharmonic emissions may be significantly amplified and thereby potentially not only have a grave impact on the devices within the installation, but may also affect other installations along the feeder. However, further studies, simulations and measurements, are needed in order to better understand the ramifications of current amplifications due to resonances.

In [40], a measurement study was conducted to investigate the transfer characteristic of a small MV/LV distribution transformer for the 2-150 kHz range. It was concluded that the supraharmonics from MV grids will be transferred 1:1 to LV grids. In the more common case, i.e. where supraharmonics originate from the LV side, the emission is effectively damped by the transformer, except at the transformer's resonance frequencies. Nonetheless, in general, little is known about the propagation of supraharmonics via cables in the grid and via transformer into other grids.

VI. Mitigation

The most practical means to mitigate supraharmonics is the placement of filters between the device and the grid in order to absorb the injected emission. For proper dimensioning of the filters, spectral impedances must be investigated and secondary emissions and resonances should be taken into account. Oversizing of the filter will increase the costs unnecessarily and undersized capacitors will be ineffective and are prone to damage. Most commonly used filters are the LCL circuit in T-structure and the CLC circuit in π-structure [39]. If supraharmonics propagate in common mode, then high attenuation of the supraharmonic emission can be achieved by implementing common mode chokes.

Semiconductor switching devices are a source of high frequency emission. However, series connections of multiple switching devices allows more complex converter topologies, which in turn provides a mean for more advanced and creative modulation strategies and switching control schemes. An overview of the different topologies and control schemes of this multi-level converter technology is provided in [13] and [16]. In these studies, it was shown via a simulation that the overall supraharmonic emission from a multi-level converter was significantly lower than for a two-level converter.

Prevention of disruptive levels of supraharmonic emission can in part be achieved via standardization. Internationally recognized standards can e.g. provide emission and immunity limits for devices, and/or create a designated frequency band to 'dump' supraharmonic emission in order to reduce the probability of EMI. Arguably, prevention is better than mitigation, thereby underlining the importance of pragmatic, and well researched standardization work.

VII. Summary and conclusion

Standardization regarding high frequency disturbances in the range of 2-150 kHz, a.k.a. 'supraharmonics', is progressing relatively fast. However, it is not straight forward to set-up standards, due to the lack of knowledge and controllability of the LV harmonic grid impedances, and the fact that the supraharmonic emission of a device is highly sensitive to a number of factors such as e.g. its internal circuit topology, and/or the presence of other devices. For supraharmonics, the total emission from an installation at the point of connection decreases as the number of supraharmonic emitting sources increases. Moreover, the emission from devices will flow for a significant part between neighbouring power electronic equipment within an installation due to the low impedance path induced by capacitors in the EMC filters of the devices, and only a small part of the emission is expected to flow towards the grid. When a large number of power electronic devices are connected to the same installation, harmonic resonances could be induced due to the capacitance in the EMC filters of the devices and the inductance of feeders and transformers in the grid. However, further research is required to determine if amplification of emission due to resonances in the low-voltage grid is a concern. In general, most research on this topic has been conducted empirically via measurements and/or simple models. However, more extensive analytical models with sufficient detail have to be developed for equipment and low-voltage networks in this frequency range to increase understanding of the practical impact on end-user equipment and assets in the grid.

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