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Impact Studies of Connecting Tuned Harmonic Filters onto a Brazilian Wind Farm

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Abstract. Wind farms are power generation complexes with nonlinear characteristics. It is well-known that such facilities are potential sources of harmonic current injection upon the network. In this sense, in cases where limits established by the regulatory agencies are exceeded, filtering strategies must be provided. Under these circumstances, passive filters are a widely employed solution for bringing harmonic distortion levels to within standard limits. However, it is recognized that the connection of passive filters can influence the characteristics of the system, causing resonances and even the intensification of harmonic distortions at the connection point between the wind farm and the external network. Therefore, this paper aims at evaluating the impacts of tuned harmonic filters on grid resonance characteristics and harmonic distortion levels from a wind farm. In this way, based on measurements of currents from an existing Brazilian wind power plant, computational studies are performed in accordance with the guidelines given by Brazilian regulations.

Keywords Wind farms, harmonic distortions, impact studies, resonances, tuned harmonic filters.

1. Introduction

The concerns regarding climate change, sustainability and efficiency improvements, along with the development of new technologies of materials, have greatly driven the increased penetration of renewable sources of energy connected to electrical power systems [1], [2]. In this sense, from among the different types of energy resources, emphasis is placed on wind power generation, for which the attractions associated with it are widely known and discussed in the literature [3]. Notwithstanding this recognition, it is noteworthy that the aforementioned complexes are potential sources of disturbances that affect the electric power quality due to their topology and operational characteristics [4].

In this context, several problems may occur due to the operating philosophy of the wind turbines. The intermittent wind itself may cause voltage and power fluctuations in the connecting busbar. In addition, modern wind farms are typically composed of electronic converters for coupling, as well as reliable operation of the plant. Indeed, converters are the main cause of harmonic current generation in these complexes [4]. Moreover, with the advent of IGBT and GTO semiconductor-based technologies, the levels of harmonic distortions can be further intensified, bringing major concerns to the regulatory agencies at present [5], [6].

In fact, there exist a number of references concerning the standardization associated with connecting wind farms. In this sense, recommendations regarding the reference values for the harmonic distortion conformity indicators are given, as well as the guidelines for reducing impacts caused by new facilities connections [7]–[9]. In Brazil, the National Electric-System Operator (ONS) is responsible for managing the power quality indicators of the interconnected networks [10], as well as for proposing guidelines for connecting wind farms to the national grid [11]. In this sense, once the limit violation for the harmonic distortions is verified at the point of common coupling (PCC) between the wind farm and the interconnected system, mitigating strategies must be applied accordingly.

In order to make the levels of harmonic distortions compatible on wind farms, two approaches may be employed depending on the nature and source of the problem. The first solution is related to the design of the whole plant to avoid resonances at typical harmonic frequencies. In fact, through intelligent system design, harmonic issues can be effectively suppressed by employing special equipment and adjusting the control of converter bridges to avoid high levels of distortions [12]. Alternatively, aiming at mitigating the disturbances of an existing wind power plant, harmonic filtering strategies are widely employed, which may be composed of active or passive-based components [13].

The active filter is an effective solution for mitigating voltages or currents harmonic distortions. Moreover, due to the increase in new converter technologies applied to the wind turbines, this strategy can be implemented directly to the converter control, reducing the need for external devices [12]. However, even though there exist benefits linked to this technology, its application may result in higher losses when compared to the classical passive-based filter [13]. In addition, when connected to resonant networks, the active filter may cause distortions at high frequencies, leading to harmonic instability [14].

Concerning passive harmonic filters, which are the subject of this paper, these are traditionally used to mitigate harmonic distortions on wind farms as they present a satisfactory cost-effective ratio. However, passive filters can also have a number of disadvantages depending on their topology and composition [13]–[15]. In this context, emphasis is placed on the fact that this strategy can cause resonances at other frequencies. It may also impact on harmonic levels by neglecting those issues in studies prior to the connection of the filter [12].

Given the aforementioned, this paper is aimed at investigating the impacts of connecting passive tuned harmonic filters on the grid-resonance characteristics and the overall harmonic distortions from a wind farm. In this context, by using measurements of currents from a Brazilian wind power plant, computational studies are performed on HarmZs software in accordance with the Brazilian regulatory requirements.

2. Connecting Tuned Harmonic Filters in Wind Farms

In order to connect passive tuned harmonic filters (THF) to wind power plants, it is imperative to follow the requirements for connecting this device to the grid according to the national regulations, as well as to consider their impacts on the operational characteristics of the accessed network. In this sense, a brief description about the tuned harmonic filters is given in this section, in addition to a summary about the Brazilian national standards and recommendations that deal with the theme.

A. Overview of tuned harmonic filters

Tuned harmonic filters are composed of series connected inductors-capacitors that are designed to create a resonant circuit at a given frequency. In this way, the filter provides a low impedance path at the tuning frequency for the circulation of harmonic currents, preventing their propagation to the network [13]. The diagram in Fig. 1 illustrates the classical arrangement of a grid-connected tuned harmonic filter for the mitigation of disturbances arising from a generic harmonic source.

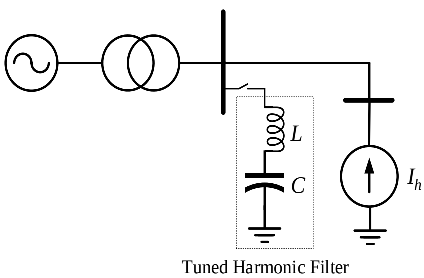

Fig. 1. Representation of a grid-connected tuned harmonic filter.

In this way, the filter tuning frequency can be obtained from (1).

$$\boldsymbol{f_{tuning} = \frac{1}{2\pi\sqrt{LC}}} \quad (1)$$

One should note that the impedance of the tuned harmonic filter has a resistive feature at the desired tuning frequency due to the inductor inherent characteristics. In addition, considering the tuning frequency as a reference, the filter presents inductive features for higher frequencies and capacitive for lower harmonic orders. Therefore, at the fundamental frequency, the filter can provide reactive power support if required.

Notwithstanding the acknowledgment that this mitigation solution is widely used on wind farms, emphasis is given to the fact that these devices can cause a number of harmful effects to the plant [14]. In this context, highlighted herein are the problems associated with new resonances at other harmonic frequencies, which may lead to increased distortions that propagate to the connecting network [12].

B. National standards and recommendations concerning harmonics

In order to connect a brand new wind farm to the Brazilian National Grid, harmonic performance studies should be carried out by the accessing agents in accordance with the guidelines proposed by the ONS 009/2016 technical report [11]. In this sense, to prevent harmonic current propagation from wind farms to the national grid, reference values must be complied in the studies considering each harmonic order *h* and the total harmonic distortion (THD). These limits are given on Table I [10].

Table I. – Individual harmonic limits and THD%

13,8 kV ≤ U < 69 kV				U ≥ 69 kV			
h odd		h even		h odd		h even	
order	limit	order	limit	order	limit	order	limit
3 to 25	1.5%	all	0.6%	3 to 25	0.6%	all	0.3%
≥ 27	0.7%			≥ 27	0.4%		
THD% = 3%				THD% = 1.5%			

Therefore, if a limit violation occur, filtering approaches should be readily proposed in the initial studies. In this way, it is noteworthy that the recommendations concerning tuned harmonic filters suggest that these must be represented by their respective parameters, considering their interactions with other components present in the vicinity of the wind farm, such as capacitor banks and inductors.

With regard to tuned filters in even orders and higher than the 13th, one notes that their implementation is only encouraged when the violation of limits are observed in the voltage measurement campaigns. Under these circumstances, filters should be connected in accordance with the standard requirements, otherwise the plant cannot operate at full capacity [11].

3. Electric Power System Implementation

In this section, the parameterization of the electrical system implemented in the computational studies is given. It is noteworthy that the wind farm emulated is based on a northeastern Brazilian power plant. In this way, from actual measurements in the field, it has been found that a limit was violated. Therefore, a harmonic filtering strategy was required, which motivated the accomplishment of the studies presented in this paper.

Regarding the computational modeling, significance is given to the fact that the studies must be conducted in accordance with the following premises [11]:

1) The wind farm and the national grid representations are performed based on the guidelines given in [11];
2) The HarmZs software, provided by the Electrical Energy Research Center (CEPEL), is used for electrical system modeling;
3) The external grid harmonic impedances are obtained based on N-side polygon representation;
4) According to the guidelines, the wind turbines are modelled as constant harmonic current sources;
5) The basic data files for the studies, as well as the parameters of the equivalent external network, are available for public reference in [16]. These are the following: 2020.sav, 2021.sav, 2022.sav, 2023.sav, and 2024.sav. Each file covers three different load conditions: light, medium and heavy loading;
6) N-1 contingency analysis were carried out for the external network covering up to the third PCC neighborhood;
7) The percentage and per unit (pu) parameters are referred to by their respective nominal voltage and power-base of 100 MVA;
8) No background disturbances from the external network has been considered in the study.

Table II and Table III show the maximum and minimum short-circuit levels at the PCC. These data were obtained through the ANAFAS software provided by CEPEL.

Table II. – Maximum PCC short-circuit level

Short-circuit	Current (kA)	Power (MVA)
Three-phase	13.820	825.82
Single-phase	14.540	868.85

Table III. – Minimum PCC short circuit level

Short-circuit	Current (kA)	Power (MVA)
Three-phase	6.260	374.07
Single-phase	7.440	444.58

The wind farm internal network is shown in Fig. 2, while the filter-connecting site is presented in more details in Fig. 3. It should be noted that for the purposes of the analysis, the tuned filters are allocated to the secondary of the transformer that connects the AG08 wind power generator. Parameters are shown on Tables IV and V. The wind farm is composed of smaller groups of wind turbines, which are called Strings. In the same way, each String is composed of groups of circuits (two or three).

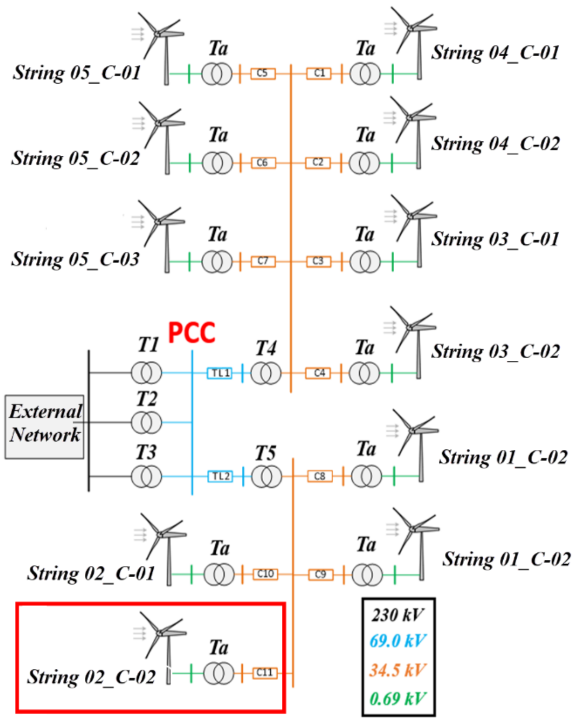

Fig. 2. Wind power plant representation.

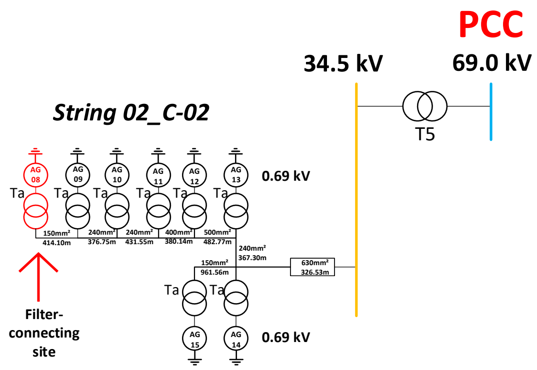

Fig. 3. Filter connecting busbar (String 02_Circuit-02).

Table IV. – Parameter of the transmission lines and cables

Symbol	R_1 (%)	X_1 (%)	B_1 (%)	R_0 (%)	X_0 (%)	B_0 (%)
TL1	1.113	4.882	0.092	3.054	18.557	0.051
TL2	1.198	2.906	0.051	2.318	10.795	0.029
C1	3.053	4.562	0.633	-	-	-
C2	1.139	2.000	0.324	-	-	-
C3	0.657	1.153	0.187	-	-	-
C4	0.228	0.400	0.065	-	-	-
C5	2.978	3.539	0.491	-	-	-
C6	1.842	2.752	0.382	-	-	-
C7	2.681	3.186	0.442	-	-	-
C8	0.901	1.581	0.256	-	-	-
C9	1.493	2.621	0.425	-	-	-
C10	0.874	1.543	0.249	-	-	-
C11	0.201	0.353	0.057	-	-	-

Table V. – Parameters of the Transformers

Transformer	Nominal power (MVA)	Nominal voltage (kV)	X%	Winding Connection
T1	150	230/69	8.8	Δ/Yn
T2	150	230/69	8.8	Δ/Yn
T3	150	230/69	8.8	Δ/Yn
T4	100	69/34	12.5	Δ/Yn
T5	70	69/34	12.5	Δ/Yn
Ta	2.35	34/69	493.61	Δ/Yn

For calculating the voltage harmonic distortion, the computational study requires the input of currents produced by the wind turbines. In this way, to achieve this goal, current measurements of the wind turbines were carried out according to the guidelines presented in [9]. Having in mind that the wind turbines of the plant are similar, the harmonic currents measured in a single wind turbine of each string were used and also applied to the others (same string). Therefore, the current measurements from a single turbine of the Strings 01 and 02 are shown on Table VI. In this way, since the currents measured at frequencies above 1500 Hz are null, these were not presented herein. Besides, the per unit (pu) base currents are their respective rated current.

Table VI. – Harmonic current measurements of Strings 01 and 02.

Harmonic order	Frequency (Hz)	I_h (pu) (String 01)	I_h (pu) (String 02)
2	120	1.38E-04	1.48E-04
3	180	1.30E-04	1.88E-04
4	240	7.80E-05	8.20E-05
5	300	1.52E-04	1.52E-04
6	360	8.20E-05	8.00E-05
7	420	2.30E-04	1.88E-04
8	480	6.40E-05	6.40E-05
9	540	6.40E-05	6.80E-05
10	600	5.40E-05	6.00E-05
11	660	3.40E-05	5.00E-05
12	720	4.40E-05	4.40E-05
13	780	3.80E-05	7.20E-05
14	840	4.40E-05	4.40E-05
15	900	3.00E-05	3.20E-05
16	960	0.00E+00	0.00E+00
17	1020	0.00E+00	0.00E+00
18	1080	0.00E+00	0.00E+00
19	1140	4.60E-05	5.00E-05
20	1200	0.00E+00	2.00E-05
21	1260	2.80E-05	2.00E-05
22	1320	0.00E+00	0.00E+00
23	1380	0.00E+00	0.00E+00
24	1440	5.80E-05	4.40E-05
25	1500	6.20E-05	6.00E-05
26-50	1560-3000	0.00E+00	0.00E+00

4. Case Studies

This section presents case studies concerning the insertion of tuned harmonic filters in order to attain the harmonic distortion levels that conform to the required limits.

First of all, the grid presented in section 3 (Fig. 2) was simulated considering that the tuned harmonic filters are switched off. In this way, it was found out that a limit violation occurred at the 4th harmonic order (240 Hz). Therefore, a harmonic filtering strategy was required, which motivated the accomplishment of the studies presented herein.
In this way, two case studies are evaluated, which are directly linked to the filter tuning frequencies. The first case is based on the insertion of a filter tuned at the violated order (4th harmonic order). The second study comprises of filter tuning at various frequencies in order to identify the best solution to cope with the matter established herein.

A. Tuned harmonic Filter - 4th Order

The simplest and most intuitive filtering solution is based on the implementation of a tuned harmonic filter at the 4th order (240 Hz), so as to address the problem under discussion. Therefore, a passive harmonic filter with 1.172pu inductive reactance and 18.75pu capacitive reactance was firstly connected to the secondary (34.5 kV) of the AG08 wind turbine transformer, as shown in Fig. 3. Therefore, Fig. 4 shows the voltage harmonic spectrum at the PCC before and after connecting the filter.

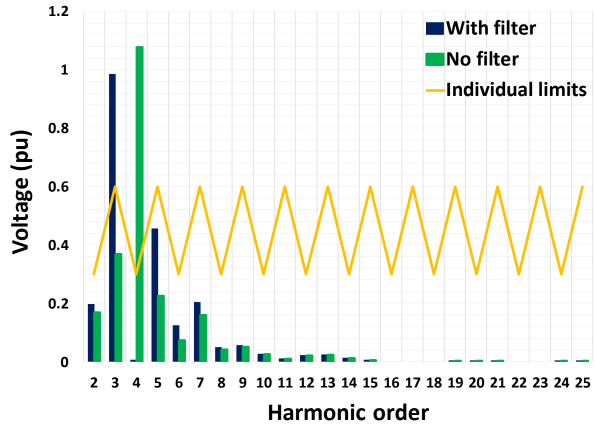

Fig. 4. Voltage harmonic spectrum before and after connecting the 4th order tuned filter.

Based on Fig. 4, in fact, the filter is capable of attenuating the 4th harmonic order precisely, for which the percentage is considerably lower than the required limits. However, it is noteworthy that the filter caused an increase at the 3rd harmonic order to 0.99%, resulting in limit violation for this order. This is possibly due to existing resonances on the circuit.

In this sense, in order to evaluate the impacts of the filter connection on the network resonance characteristics, Fig. 5 presents the impedance-frequency response at the PCC, before and after connecting the filter at the 4th order.

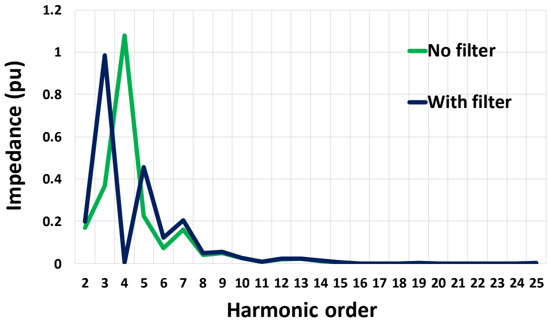

Fig. 5. Impedance-frequency response before and after connecting the 4th order tuned filter.

Based on Fig. 4, one notes that before the insertion of the filter, the grid presents a limit violation at 4th order (240 Hz). Although high values for this order are not common in electrical grids, sometimes it may occur due to a parallel resonance (Fig. 5) that, when composed with the currents arising from the wind farm, results in the 4th order limit violation. In addition, for determining the harmonic voltage distortions, a number of different operating states of the external network were considered, whose most critical scenario has resulted in the levels herein presented.

After connecting the filter, the characteristic of maximum impedance-frequency shifts to the left, while its minimum value is centered in the filter tuning frequency. In fact, this is due to the filter inherit characteristics that cause changes in the equivalent impedance at the connecting busbar.

Therefore, since the solution herein given is not effective in terms of mitigating all harmonic distortion orders accordingly, a second case study is carried out, which consists of evaluating different tuned harmonic filters in order to point out the best solution to the problem addressed herein.

B. *Tuned harmonic Filters - Different Tuning Frequencies*

In this section, the performance of the filtering process is investigated considering different filter tuning orders; they are 3rd, 5th, 7th, 11th and 13th. It is noteworthy that the studies of the aforementioned filters are performed punctually, i.e., considering each filter as independently connected to the system. Table VII shows the characteristics of the filters.

Table VII. – Tuned harmonic filter parameters for multiple orders.

Parameters (pu)	THF3	THF5	THF7	THF11	THF13
X_c	18.75	18.75	18.75	18.75	18.75
X_L	2.084	0.750	0.382	0.154	0.110

In order to evaluate the performance of the filters in terms of their accuracy in making the harmonic distortion indicators compatible, Table VIII presents the individual percentages resulting from the insertion of each filter. Noteworthy here is that the highlighted values (red) correspond to the limit violations according to national standards.

Table VIII. – Individual harmonic distortion for each THF.

Harmonic order	THF3 (%)	THF5 (%)	THF7 (%)	THF11 (%)	THF13 (%)
2	0.209	0.193	0.191	0.189	0.189
3	0.009	0.651	0.560	0.528	0.523
4	0.230	0.131	0.296	0.672	0.769
5	1.234	0.010	0.093	0.123	0.128
6	0.091	0.157	0.019	0.037	0.039
7	0.178	0.281	0.024	0.084	0.091
8	0.044	0.056	0.185	0.019	0.022
9	0.051	0.059	0.097	0.018	0.025
10	0.025	0.028	0.037	0.004	0.010
11	0.009	0.009	0.011	0.007	0.003
12	0.020	0.021	0.024	0.055	0.006
13	0.023	0.023	0.025	0.044	0.037
14	0.023	0.024	0.026	0.044	0.037
15	0.013	0.013	0.014	0.019	0.037
16	0.004	0.004	0.004	0.005	0.007
17	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000
20	0.001	0.001	0.001	0.001	0.001
21	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000
25	0.001	0.001	0.001	0.001	0.001

Given the aforementioned, one can infer that for all filters presented, at least one limit violation has occurred, except for the filter tuned at 7th order. In this sense, Fig. 6 illustrates the voltage harmonic spectrum before and after the insertion of the mentioned filter.

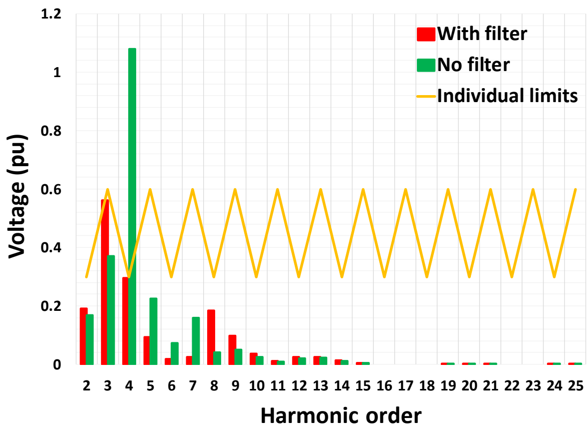

Fig. 6. Voltage harmonic spectrum before and after connecting the 7th order tuned filter.

Regarding the impedance-frequency response for the 7th harmonic filter, this is shown in Fig. 7.

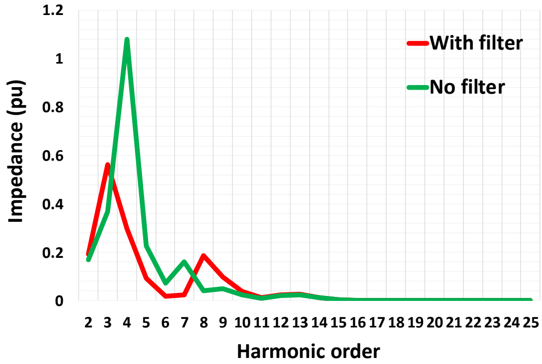

Fig. 7. Impedance-frequency response before and after connecting the 7th order tuned filter.

Based on Fig. 7, one notes that although the filter has changed the resonance characteristics of the network presented herein, the 3rd order resonance resulting from the filter connection was not sufficient to violate the established limits.

Moreover, it should be pointed out that the simulated cases covered different loading conditions (light, medium and heavy) from 2020 to 2024, as well as the N-1 contingency analysis covering up to the 3rd PCC neighborhood. For this reason, it can be inferred that, among the solutions herein presented, the 7th order harmonic filter presented itself as the most suitable solution for maintaining harmonic distortions under the established limits, since it was able to reduce the most severe distortions and eliminate the need for using multiple filters.

5. Conclusion

The objective of this paper was to evaluate the impacts of connecting passive tuned harmonic filters on the grid-resonance characteristics and the overall harmonic distortions from a wind farm. In this context, from measurements from a Brazilian wind power plant, computational studies were performed in accordance with national regulations.

In this sense, two case studies were evaluated in order to mitigate the 4th order harmonic distortions arising from the wind farm. The first study was based on the insertion of a tuned harmonic filter on the violated order. The second solution was based on different filter tunings in order to identify the best solution to address this matter.

The results have shown that the 4th order filter caused a resonance in the 3rd order, implying the limit violation at this order. Therefore, after evaluating the insertion of different tuned harmonic filters, one finds that the 7th order filter was able to solve the problem focused upon herein.

Acknowledgement

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