Z-Source Flyback PFC Rectifier for Energy Storage Systems

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***Abstract*—This paper proposes a wide range high step-down gain flyback power factor correction rectifier (PFC) based on the flyback DC-DC converter. The proposed rectifier is composed of a step-down Z-source network at the AC to DC stage, followed by a flyback chopper. The proposed PFC rectifier offers better input and output waveform qualities in comparison to the conventional buck-boost and flyback PFC rectifiers, because of continuous input current. Also, it ensures high power factor (PF) operation and low harmonic contents over a wide range of load and source variations with galvanic isolation. These features are practically of interest for a battery charging system. Furthermore, the proposed PFC rectifier allows for increasing the switching frequency due to a higher duty cycle possible for the same voltage gain than the competitors. Finally, the unity power factor operation is simply possible by just using a simple single loop voltage controller. A test bench of the proposed PFC rectifier is designed for performance evaluation in PLECS software. Also, the performance of the converter is experimentally confirmed by tests on a 230 V_{rms} to 48 V_{dc} rated at 200-W laboratory prototype.**

Keywords—energy storage, flyback, power factor correction, rectifier, Z-source

I. Introduction

PFC rectifiers are used in many industrial applications such as battery chargers, LED drivers, and telecom power supplies [1], [2]. A battery charger must offer high efficiency and reliability with a near to unity power factor current drawn through the input source. PFC rectifier aims to improve the power quality requirement of the grid and also to extend the lifetime of the battery used in an energy storage system [3]. PFC rectifiers have recently attracted attentions to be employed as the battery chargers due to low harmonics injection to the grid, high power factor, high-quality output voltage and low electromagnetic interference. The PFC rectifiers are also mainly utilized as the power supply unit (PSU), electric vehicles (EVs) chargers, and wind turbines[4]. As seen in Fig. 1, the main configuration of the battery charger including of a diode bridge, a boost PFC circuit and a step-down DC-DC chopper. The boost PFC rectifier is mostly known as the best solution for power factor correction in many applications owing to entirely sinusoidal current waveform drawn through the input and considerably high power factor[5]. But, the output voltage of boost PFC rectifier is higher than the peak of AC input voltage, while most of the batteries require lower voltages than that of the AC input. This necessitates employing an additional DC-DC converter to decrease its output voltage for the applications with low voltage requirements. The buck rectifier provides the feasibility of voltage step-down gain ratio. Unfortunately, the buck-type PFC rectifier cannot provide as high-quality waveforms as that of the boost-type one. The input current low total harmonic distortions (THD) and PF of the buck-type PFC rectifier are drastically worse compared to the boost-type one resulting in lower applicability of this PFC rectifier. As seen in Fig. 2, a destructive phenomenon is known as the dead angle that occurs as to the buck PFC rectifier, which decreases the quality of the sinusoidal waveform of the AC input current. In other words, since the output voltage of the buck PFC rectifier decreases to lower values than the value of sinusoidal input voltage, the series switch of the buck converter cannot turn on resulting in the interruption in the AC input current [6][7]. In addition to the dead angle, the absence of the input inductor significantly decreases the input current THD compared to the boost-type PFC rectifier. The conventional buck-boost PFC rectifier can provide higher and lower value of voltages from the AC input voltage. This PFC rectifier improves the performance and quality of the waveforms of the other solutions. Although, lack of the input inductor in this rectifier still produces AC input current distortion. Continuous input current capability in many industrial applications is an essential factor in improving the performance of the different converters. High quality input current is main factor in the industrial applications [8]–[12]. Moreover, reverse output voltage polarity and the need for the floating drive for its power switch are the other shortcomings of buck-boost PFC rectifier [13]. Also, some industrial applications like telecom power supply and battery charger need a low output voltage over a wide input voltage, which is set in 48 V_{dc}. The conventional buck-boost converters cannot provide high step-down gain. So, the duty cycle in these converters is very low. Also, the high value of switching frequency reduces the switch conduction time. So the power loss is increases. This problem increases the switching loss and limits the switching frequency [1].

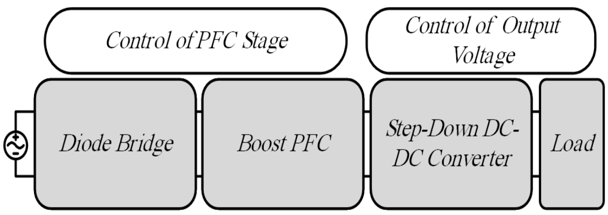

Fig. 1 Conventional two stage power supply

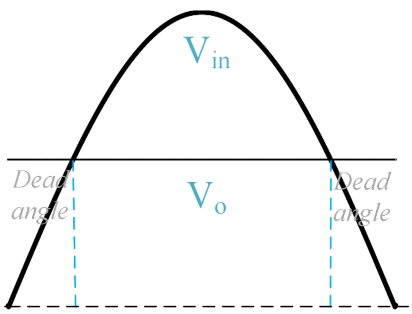

Fig. 2 Dead angle of buck-type PFC rectifier.

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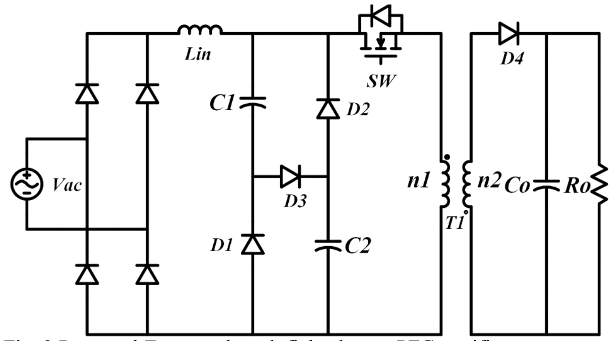

Fig. 3 Proposed Z-source-based flyback type PFC rectifier.

To address these issues, this paper proposes an improved high gain step-down PFC rectifier implemented as a flyback converter. The proposed rectifier offers continuous input current, unlike conventional flyback PFC rectifier. According to the voltage buck or boost ability of the Z-source networks as in [14] the proposed PFC rectifier employs a buck-type Z-source network to better adjust the output voltage. The idea of the new configuration for the PFC rectifier mainly focuses on the improvement of the quality of the input and output side waveforms. The performance analysis and modes of the operation are presented in the following and verified through some simulations in PLECS software. Also, the performance of the proposed rectifier, is experimentally endorsed by tests on a 230 V_{rms} to 48 V_{dc} 200-W AC-DC prototype.

II. Proposed PFC Rectifier

A. Circuit Configuration

The proposed PFC rectifier configuration includes a diode bridge, a Z-source network and, a flyback converter, as shown in Fig. 3. The Z-source network is constructed from an input inductor, and a set of diode-switched-capacitors already proposed in [14]. The input inductor of the proposed rectifier lets reduce input current THD and increases the power factor, unlike the conventional buck-boost and flyback PFC rectifiers. Generally, due to the possibility of increasing the switching frequency, the capacitors of the Z-source network are considerably low to not contribute to the power loss of the converter. Also, the flyback converter is utilized as the last stage of power conversion to adjust the input current and output voltage. The performance and operation principles of the proposed PFC rectifier are analyzed in the following.

B. Operation Principles

Since the operation modes of the proposed PFC rectifier in each half period of the input voltage are the same, thus for the sake of simplicity, only positive half period operation modes are explained in the following. The proposed rectifier is operated in discontinuous conduction mode (DCM) mode. By operating the rectifier in DCM mode, many advantages can be obtained, like as inherent high value of the PF and low THD. Also, the turn-on switching losses of high frequency switch and the reverse recovery problem of the output diodes are remarkably reduced [15].

a) Mode I [0~DT_s]:

As seen in Fig. 4 (a), the switch *SW* is turned on and the diodes D_3 and D_4 are reversed biased, while D_1 and D_2 conduct the current pass. The input and output inductance, i.e. L_{in} and L_m of transformer T_1, are charged in this mode and their currents increase with a constant ramp. The voltage and current equations of this mode are obtained as in (1),

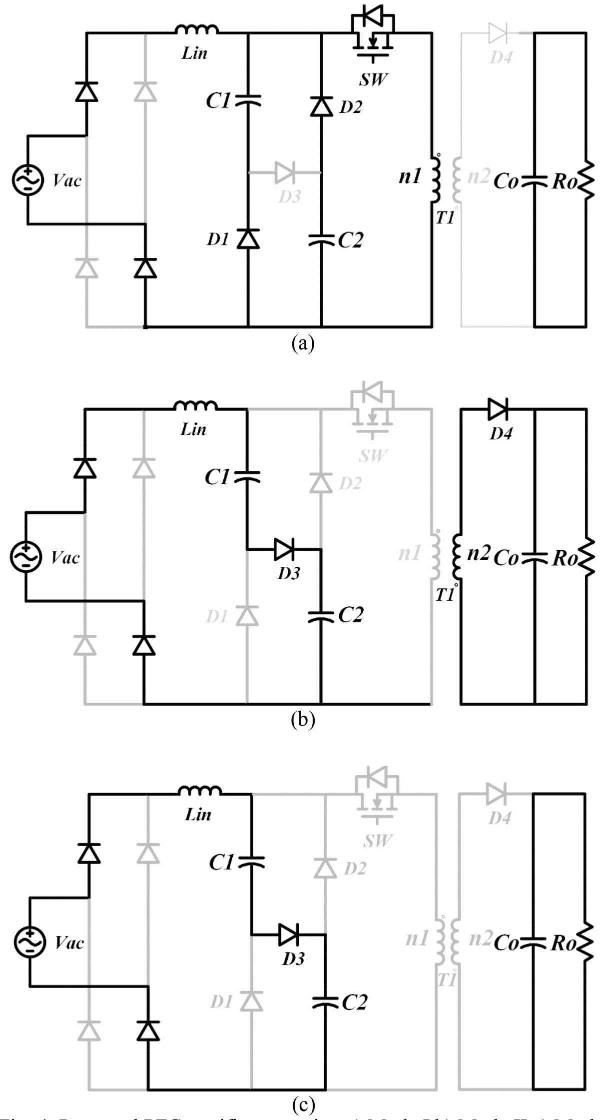

Fig. 4. Proposed PFC rectifier operation a) Mode I b) Mode II c) Mode III

$$\begin{cases} \hat{V}_{Lin} = \hat{V}_{in} - \hat{V}_{c_{1,2}} \\ \hat{V}_{n1} = \dfrac{n_2}{n_1}\hat{V}_{n2} = \hat{V}_{c_{1,2}} \\ \hat{I}_{in} = \hat{I}_{Lin} \\ \hat{I}_{n1} = \hat{I}_{in} + 2\hat{I}_{c_{1,2}} \\ \hat{I}_{n2} = 0 \\ \hat{I}_{C_o} = +\dfrac{\hat{V}_o}{R_o} \end{cases} \tag{1}$$

This mode ends when the switch is turning off.

b) Mode II [DT_s~$D'T_s$]:

As depicted in Fig. 4 (b), the switch *SW* is turned off and at the same time, the diodes D_3 and D_4 are forward biased and conduct, while the diodes D_1 and D_2 are blocking the capacitors C_1 and C_2 voltages. The inductors L_{in} and L_m are discharged and their currents decrease. The inductor L_m current maintains higher than zero in this mode. The voltage and current equations of this mode are given as in (2).

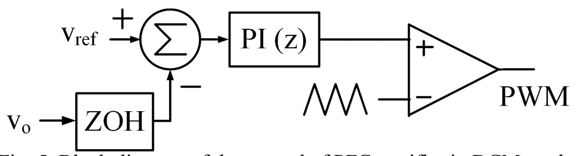

Fig. 5. Block diagram of the control of PFC rectifier in DCM mode.

$$\begin{cases} \hat{V}_{Lin} = 2\hat{V}_{c_{1,2}} - \hat{V}_{in} \\ \hat{V}_{n1} = \dfrac{n_2}{n_1}\hat{V}_{n2} = \hat{V}_o \\ \hat{I}_{in} = \hat{I}_{Lin} = \hat{I}_{c_{1,2}} \\ \hat{I}_{c_o} = \hat{I}_{n2} - \dfrac{\hat{V}_o}{R_o} \end{cases} \qquad (2)$$

c) *Mode III [D'Ts~Ts]:*

In this mode, the operation of the proposed PFC rectifier is similar to mode II, with the only difference that the L_m current becomes zero, which translates to DCM operation of the flyback converter. However, the input inductor L_{in} current decreases to a final value higher than zero in this mode. This mode is shown in Fig. 4 (c). According to this figure, one can write as in (3),

$$\begin{cases} \hat{V}_{Lin} = 2\hat{V}_{c_{1,2}} - \hat{V}_{in} \\ \hat{V}_{n1} = \hat{V}_{n2} = 0 \\ \hat{I}_{in} = \hat{I}_{Lin} = \hat{I}_{c_{1,2}} \\ \hat{I}_{n1} = \hat{I}_{n2} = 0 \\ \hat{I}_{c_o} = +\dfrac{\hat{V}_o}{R_o} \end{cases} \qquad (3)$$

The voltage gain ratio equation of the proposed PFC rectifier is attained by exerting a volt-second rule on the voltage across the input and L_m inductors in modes I, II and III. The voltage gain equation known as the ratio of peak output to peak input voltages in terms of the duty cycles (D and D') is given in (4).

$$\begin{aligned} &\frac{\hat{V}_o}{\hat{V}_{in}} = \frac{D}{((D'-D)\times(2-D))}\frac{n_2}{n_1} \\ &D'|_{CCM} = 1 \\ &D'|_{DCM} = D + \sqrt{\frac{2L_m}{T_s R}} \end{aligned} \qquad (4)$$

III. Control Method

The conventional control method of the PFC rectifier scheme is known as the average current control and consists of a double closed-loop control plant. A close loop (PI) controller is employed for the output voltage regulation as the outer loop and one more controller for the input AC regulation in the inner loop. The same as the SEPIC rectifier of [15], the proposed PFC rectifier can be well operated with only a single loop control scheme for output voltage regulation without requiring any current control loop, as shown in Fig. 5. In other words, with DCM operation, the input current of the proposed PFC rectifier maintains as a pure sinusoidal waveform, due to employing an input inductor at the DC side. This lets the input current waveform to be proportionate to the input voltage waveform. Thus, the input current can synchronously track the sinusoidal form of the AC input voltage and achieve near unity power factor performance. Also, the single loop control ability translates to two fewer sensors needed for the closed-loop control procedure. As a result, only the output voltage sensor is required for the output voltage regulation.

Table I.
Simulations and Experimental Conditions.

Description	Values
Nominal power, P_o	200 W
Input AC voltage, V_{in}	230 V_{rms}
Output voltage, V_o	48 V
Switching frequency, f_s	30 kHz
Capacitors: C_1, C_2 and C_o	1 µF, 1 µF and 6.8 mF,
Input inductor (L_{in})	5 mH
Flyback transformer (L_m)	60 µH (T1=1:1)
Diodes, D_1, D_2, D_3	RHRG75120
IGBT switch, SW	IXGH48N60C3

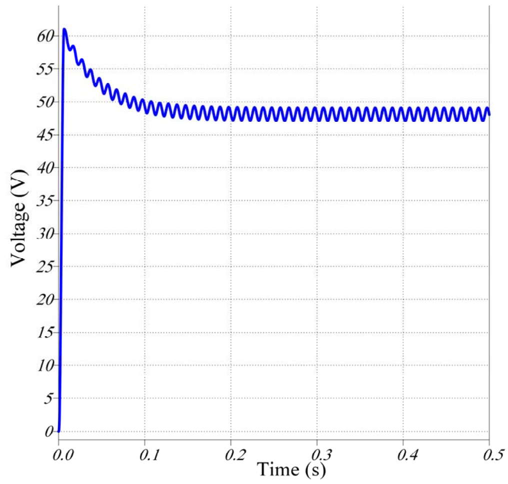

Fig. 6. Output voltage of proposed rectifier.

IV. Simulation And Experimental Results

The theoretically derived operation principles of the proposed flyback PFC rectifier is investigated in this section through a set of simulations in PLECS software. In order to better simulate the rectifier, the thermal module of the PLECS software is utilized to model the real and experimental parasitic elements of the proposed rectifier components. The simulation conditions and parameters are mentioned in Table I. In addition to the above analysis, the operation of the proposed PFC rectifier is also simulated and the results are shown in Figs. 6-8. As shown in Fig. 6, the output voltage is adjusted at 48 V_{dc}. The output voltage ripple of the proposed PFC rectifier is about 5%, which meets the needs of battery charging requirements. The input AC current and AC voltage of the proposed rectifier are shown in Fig. 7, where its THD is 4.5%. It can be seen from Fig.7 that input voltage waveform is in phase with input current waveform and is actually sinusoidal with high PF and low THD. Besides, the result of the simulations of stress voltage across the main switch and diode is shown in Fig 8. Also, the magnetizing current of the transformer is shown in Fig 8. In order to corroborate the analytical results and verify the performance of the proposed rectifier, a 200-W rectifier is implemented and the experimental results are shown in Fig. 9 and Fig. 10. The RCD snubber across the main switch is used in the experimental test porotype to elimination the voltage spike

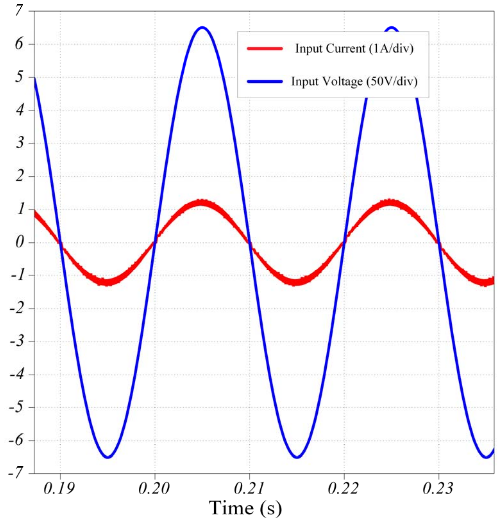

Fig. 7. Source voltage and current of proposed rectifier.

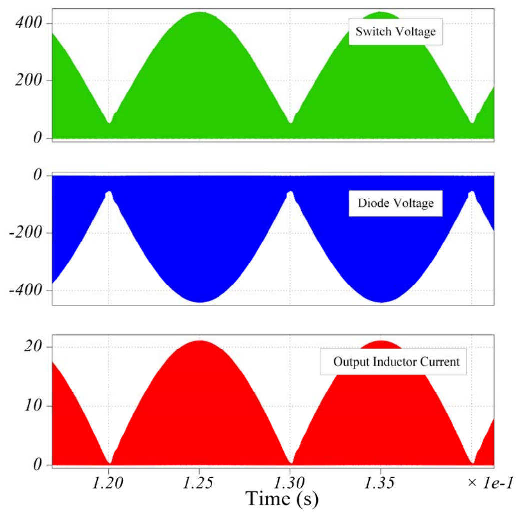

Fig. 8. Voltage stress of semiconductors and inductor current of proposed rectifier.

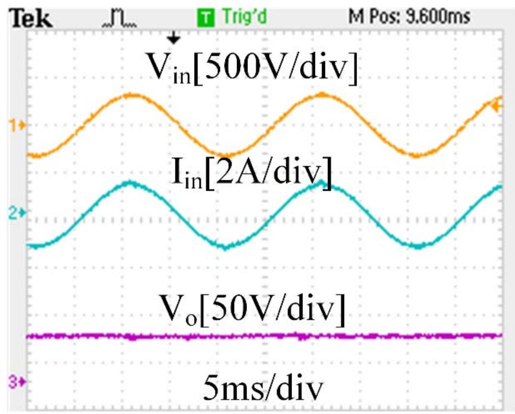

Fig. 9. Waveform of the source voltage/current and output voltage.

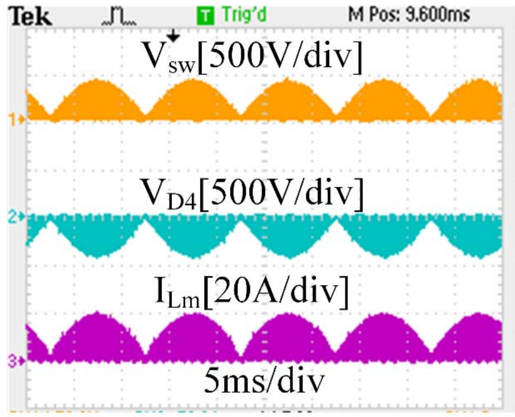

Fig. 10 Waveform of voltage stress of semiconductors and inductor current of proposed rectifier.

across the main switch. The waveforms of input source voltage/current and output voltage are presented in Fig. 9. The voltage stresses across the switch and output diode, and the inductors currents are depicted in Fig. 10. The experimental results and simulation results are similar approximately. The power factor is obtained with the various output loads as low as 40% to the nominal output power is shown in Fig. 11.

In order to verify the high-efficiency rectification of the proposed PFC rectifier, Fig. 12 is presented. The efficiency is obtained with the various output loads as low as 40% to the nominal output power.

The obtained simulation and experimental results and the above analysis show that the proposed PFC rectifier is an improved solution for the PFC rectification applications, which meets the energy storage requirements for battery charging or other applications.

In order to compare the proposed PFC rectifier with the already reported rectifiers, Table II is also presented. As can be seen from this table, the proposed PFC rectifier offers suitable input/output current/voltage characteristics which are comparable with the other PFC rectifiers. The proposed PFC rectifier provides high step-down gain with the high-quality input current. Besides the proposed rectifier guarantees galvanic isolation. Also, the proposed PFC rectifier requires an adequate number of components with the ability of AC/DC conversion using only one stage of the power converters. Conforming to the analysis results, the derived theoretical operations of the proposed rectifier are all well-

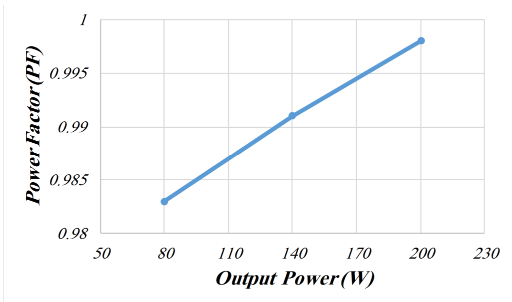

Fig. 11. The power factor diagram for various P_o.

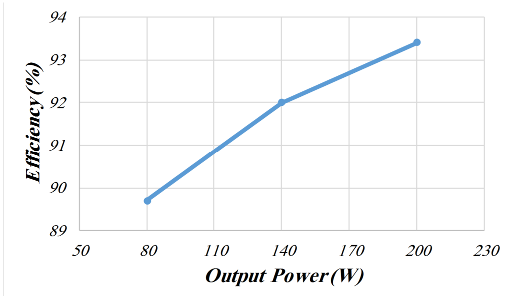

Fig. 12 The efficiency diagram for various P_o.

Table II. Comparison of reported and proposed PFC rectifier.

	Proposed	[1]	[3]	[5]	[6]	[13]	[15]
Topology	**High gain buck**	**Cuk**	**Buck+ flyback**	**Boost+ DC-DC Stage**	**Buck**	**Buck-Boost**	**Sepic**
No. of switches	1	1	4	5	2	2	2
No. of diodes	8	6	6	6	4	2	5
No. of inductances	2	3	3	4	2	3	3
No. of cores	2	3	2	3	3	2	3
No. of capacitors	3	2	2	3	3	3	2
Input voltage/output voltage	230 Vrms / 48 Vdc	230 Vrms / 48 Vdc	230 Vrms / 80 Vdc	230 Vrms / 48 Vdc	230 Vrms / 160 Vdc	110 Vrms / 48 Vdc	220 Vrms / 48 Vdc
Nominal power	200W	500W	100 W	480 W	700 W	300 W	100 W
Reported efficiency at nominal output power (%)	93.4	-	95.5	94.35	96 5	93.87	91.8
Reported THD at nominal output power (%)	4.5 %	7.35	20.7	-	23.3	9.6	1.6
Number of required sensors to good performance	1	3	2	4	1	1	1
Galvanic isolation	Available	Not available	Available	Available	Not available	Not available	Available
Input current	Continuous	Continuous	Discontinuous	Continuous	Discontinuous	Continuous	Continuous

supported by the simulations, which confirms the validity of the proposed PFC rectifier.

V. Conclusion

This paper introduced an improved high gain step down PFC rectifier integrated with a flyback converter, which brings advantages over the conventional solutions for applications such as battery charging from the AC grid. The proposed rectifier offers continuous input current, unlike the conventional flyback PFC rectifiers. This rectifier produces waveforms with much higher quality compared to its conventional counterparts. Besides, it was shown that with simple single-loop voltage control, requiring only one sensor; the near unity power factor operation is attainable. The simulation and experimental results confirm its better performance.

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