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International Conference on Energy and Environment: bringing together Engineering and Economics

Guimarães, Portugal, 18-19 June, 2015.

Vítor Monteiro, J. G. Pinto, Bruno Exposto, Delfim Pedrosa, João L. Afonso, "Multifunctional Converter to Interface Renewable Energy Sources and Electric Vehicles with the Power Grid in Smart Grids Context," ICEE International Conference on Energy and Environment: Bringing Together Engineering and Economics, Guimarães Portugal, pp.1-6, June 2015.

MULTIFUNCTIONAL CONVERTER TO INTERFACE RENEWABLE ENERGY SOURCES AND ELECTRIC VEHICLES WITH THE POWER GRID IN SMART GRIDS CONTEXT

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KEYWORDS
Electric Vehicle; Renewables; Power Converters; Smart Grids.

ABSTRACT

This paper proposes a multifunctional converter to interface renewable energy sources (e.g., solar photovoltaic panels) and electric vehicles (EVs) with the power grid in smart grids context. This multifunctional converter allows deliver energy from the solar photovoltaic panels to an EV or to the power grid, and exchange energy in bidirectional mode between the EV and the power grid. Using this multifunctional converter are not required multiple conversion stages, as occurs with the traditional solutions, where are necessary two power converters to integrate the solar photovoltaic system in the power grid and also two power converters to integrate an off-board EV battery charger in the power grid (dc-dc and dc-ac power converters in both cases). Taking into account that the energy provided (or delivered) from the power grid in each moment is function of the EV operation mode and also of the energy produced from the solar photovoltaic system, it is possible to define operation strategies and control algorithms in order to increase the energy efficiency of the global system and to improve the power quality of the electrical system. The proposed multifunctional converter allows the operation in four distinct cases: (a) Transfer of energy from the solar photovoltaic system to the power grid; (b) Transfer of energy from the solar photovoltaic system and from the EV to the power grid; (c) Transfer of energy from the solar photovoltaic system to the EV or to the power grid; (d) Transfer of energy between the EV and the power grid. Along the paper are described the system architecture and the control algorithms, and are also presented some computational simulation results for the four aforementioned cases. It is also presented a comparative analysis between the traditional and the proposed solution in terms of operation efficiency and estimated cost of implementation.

INTRODUCTION

Nowadays, the electric vehicle (EV) is considered the foremost alternative to reduce the global oil consumption associated to the transports sector (Rajashekara, 2013; Milberg and Schlenker, 2011). Therefore, with the large-scale introduction of EVs will arise new challenges to the power grids aiming to deal with the electricity market and to mitigate the energy production based in nonrenewable sources (Boulanger et al., 2011; Moses et al., 2010; Clement-Nyns et al., 2010). In order to mitigate the impact of the EVs introduction in the power grids, in terms of the energy needed to charge their batteries, it is expected an increase in renewable energy sources share, mainly solar photovoltaic and wind power systems. The conjugation of renewable systems and EVs will contribute to reduce significantly the greenhouse gases emission and to enable and magnify the smart grids and smart homes paradigms (Gungor et al., 2012; Moslehi and Kumaret al., 2010; Morgan, 2012). With the forthcoming of smart grids and EVs will also emerge a diversity of incentives and advantages towards energy saving (Inoa and Wang, 2011). In this scenario, will arise new opportunities and challenges to combine renewables and EVs towards the advances in micro-generation (Gungor et al., 2012; Lopes et al., 2009). Therefore, the end user will have the possibility to participate actively in the energy market, i.e., taking part as an energy producer or consumer. For such purpose, it will be required several developments and studies aiming the integration of these systems in the power grids.

The integration of EVs in the power grids is often associated only to the batteries charging process, which is identified in the literature as grid-to-vehicle (G2V) operation mode. However, the EV can also operate as an active element in the power grid, i.e., delivering energy back to the power grid, which is identified in the literature as vehicle-to-grid (V2G) operation mode. In the V2G operation mode the user is able to sell to the power grid part of the energy stored in the EV battery. These operation modes can be controlled in accordance with the electricity provider and the EV driver, contributing to the peak shaving and load leveling paradigms (Martins et al., 2013). Moreover, when the EV is plugged,

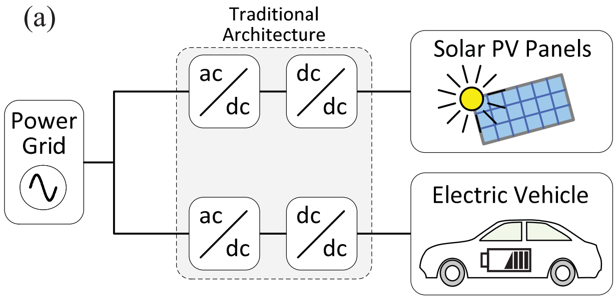

Figure 1: Integration of a solar photovoltaic system and an off-board EV battery charger in the power grid: (a) Traditional architecture; (b) Proposed architecture.

smart strategies can be defined for its operation aiming to mitigate the variability of energy production from renewable energy sources (mainly allowing to store the energy surplus) (Lopes et al., 2009; Traube et al., 2012). In this context, this paper proposes an unified system based in a multifunctional power electronics converter, which allows integrate a solar photovoltaic system and an off-board EV battery charger with the power grid. This multifunctional converter allows to deliver energy from the solar photovoltaic system to the EV or to the power grid, and exchange energy in bidirectional mode between the EV and the power grid. Using this multifunctional converter it is not required multiple conversion stages as occurs with the traditional solutions, where is required a power converter to integrate the solar photovoltaic system in the power grid and also a power converter to integrate the off-board EV battery charger in the power grid. The proposed multifunctional converter has one ac and two independent dc interfaces. Therefore, taking into account that the energy provided (or delivered) from the power grid in each moment is function of the EV operation mode and the energy produced by the solar photovoltaic system, it is possible to define strategies and control algorithms to increase the global system energy efficiency without neglecting the power quality.

SYSTEM ARCHITECTURE AND DESCRIPTION

Figure 1(a) shows the traditional architecture to integrate a solar photovoltaic system and an off-board EV battery charger in the power grid. As it can be seen are required two power converters to interface the solar photovoltaic system and the power grid, as well as two power converters to interface the off-board EV battery charger and the power grid. Analyzing this architecture, it is possible to observe that the dc-dc power converters are used to interface the solar photovoltaic system and the off-board EV battery charging station, and the ac-dc power converters are used to interface the power grid. Therefore, both ac-dc power converters are very similar and can be grouped in a single ac-dc power converter. Figure 1(b) shows the proposed architecture, which is composed by the two dc-dc power converters and by a single ac-dc power converter. Using this architecture it is possible to reduce the required hardware to integrate a solar photovoltaic system and an off-board EV battery charger in the power grid, and consequently decrease the system total cost. As the energy flows from the solar panel to the EV battery with less conversion stages the system efficiency increases. The dc-dc power converter used to interface the solar system is controlled in order to extract at each instant the maximum power from the photovoltaic panels, i.e., it is used a maximum power point tracker (MPPT) algorithm. This power converter operates in unidirectional mode. The dc-dc power converter used in the off-board EV battery charger is controlled to operate in two distinct modes. During the EV battery charging process (G2V) this converter is controlled to regulate the battery charging current and the battery charging voltage. On the other hand, when the system delivers part of the energy stored in the batteries back to the power grid (V2G) the dc-dc converter is controlled to regulate the battery discharging power (it is controlled the battery discharging current in function of the battery voltage). To accomplish with the two operation modes this power converter is bidirectional. The ac-dc power converter is used to interface the power grid and it is controlled to absorb or inject energy, depending on the power produced by the solar photovoltaic system and the EV battery charger operation mode. This power converter also operates in bidirectional mode.

CONTROL ALGORITHMS

Figure 2 shows the integration of the solar photovoltaic system and the off-board EV battery charger in the power grid through the proposed converter, where P_{PG} represents the active power in the power grid, P_{PV} represents the active power in the solar photovoltaic system and P_{EV} represents the active power in the EV. As it can be seen, the proposed converter can operate in four distinct cases: (a) Transferring energy from the solar photovoltaic system to the power grid; (b) Transferring energy from the solar photovoltaic system and from the EV to the power grid; (c) Transferring energy from the solar photovoltaic system to the EV; (d) Transferring energy between the EV and the power grid.

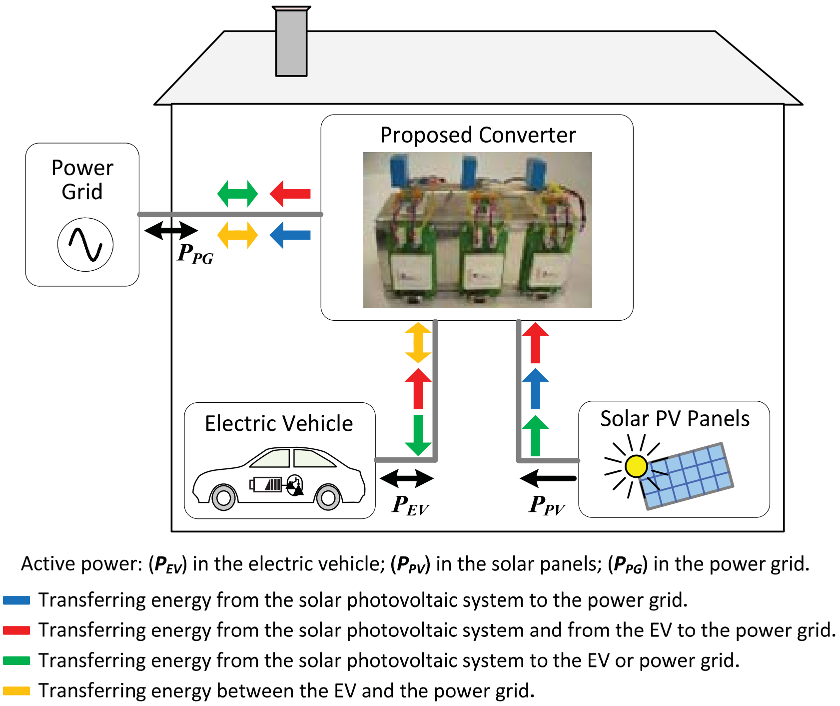

Figure 2: Integration of the solar photovoltaic system and the EV off-board battery charger in the power grid through the proposed converter.

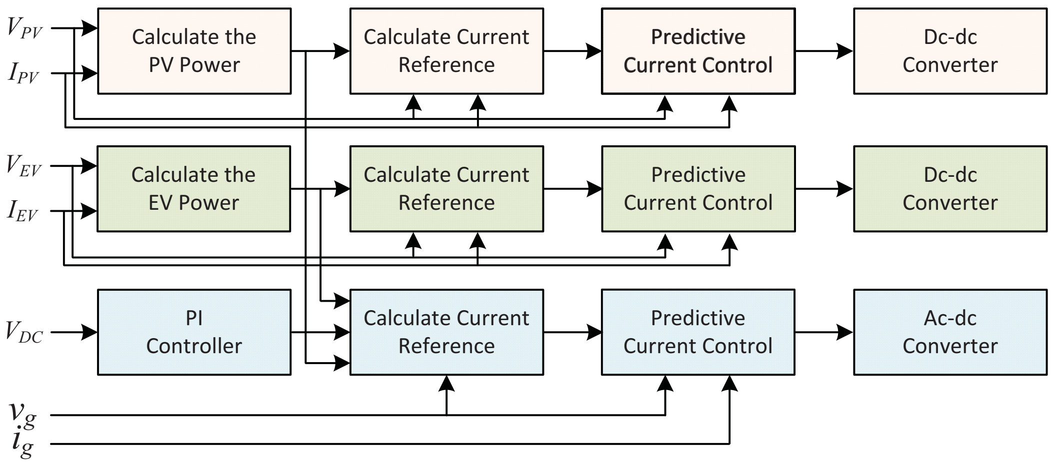

Figure 3: Block diagram of the proposed converter control algorithm.

Figure 3 shows the block diagram of the proposed converter control. As it can be seen the references of current for both dc-dc converters is calculated based in the measured currents and voltages of the solar photovoltaic system (I_{PV} and V_{PV}) and the EV (I_{EV} and V_{EV}). Using these references, the current in each dc-dc converter is controlled individually through a predictive control. On the other hand, the reference of current for the ac-dc converter is calculated based in the measured power grid current (i_g) and voltage (v_g) and the power to regulate the dc-link voltage (V_{DC}), i.e., the voltage that is common to the dc-dc and ac-dc converters. Using this reference, the current in the ac-dc converter is also controlled through a predictive control.

SIMULATION RESULTS

In this section are presented some simulation results of the proposed multifunctional converter. In a first case the multifunctional converter is only used to inject energy from the solar photovoltaic system in the power grid, i.e., the EV is not plugged. In this case, besides the ac-dc converter, it is also used the dc-dc converter with MPPT control algorithm. Figure 4 shows the power in the power grid side (P_{PG}) (cf. Figure 4(a)), the power in the EV (P_{EV}) (cf. Figure 4(b)) and the power in the solar photovoltaic system (P_{PV}) (cf. Figure 4(c)) during this case. As it can be seen, the power in the solar photovoltaic system changes according with the MPPT algorithm and the power in the power

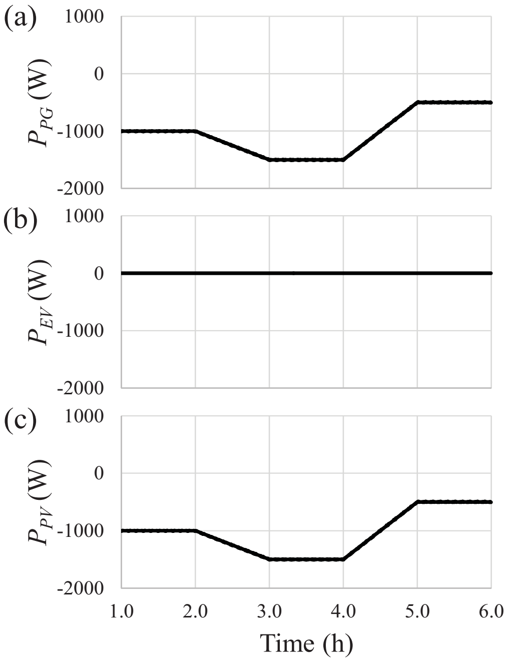

Figure 4: Simulation results representing the transfer of energy from the solar photovoltaic system to the power grid.

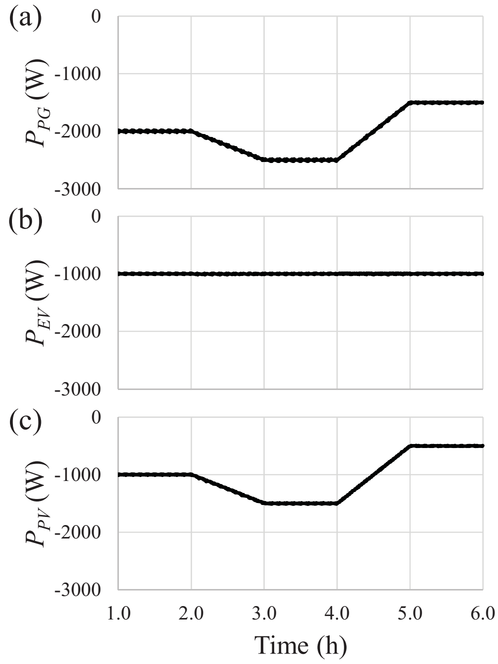

Figure 5: Simulation results representing the transfer of energy from the solar photovoltaic system and from the EV to the power grid.

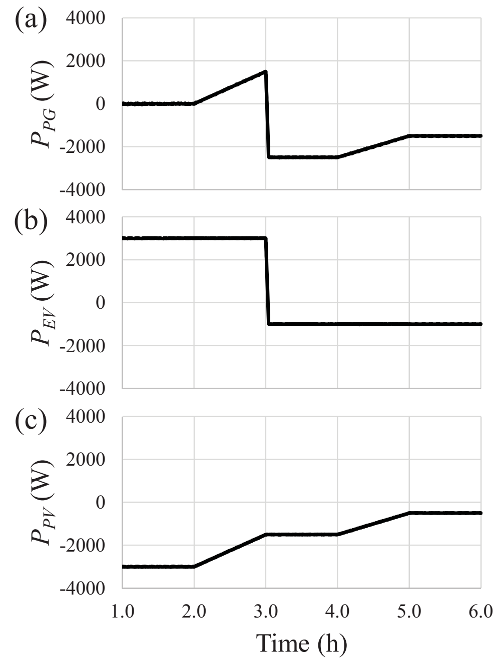

Figure 6: Simulation results representing the transfer of energy from the solar photovoltaic system to the EV or power grid.

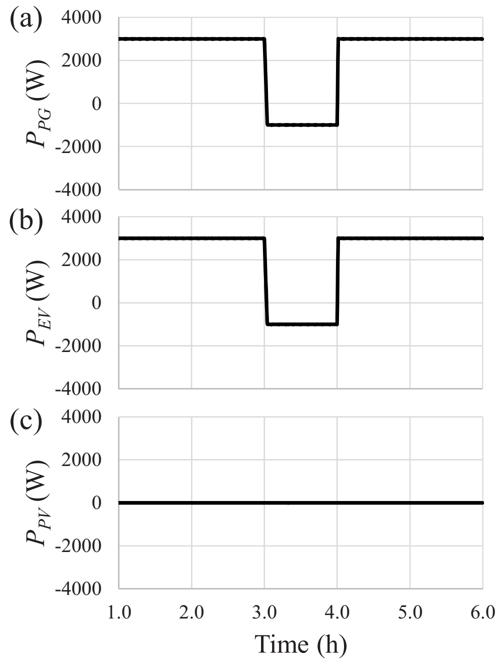

Figure 7: Simulation results representing the transfer of energy between the EV and the power grid.

grid also changes according with the power extracted from the solar photovoltaic system. In a second case the proposed multifunctional converter is used to inject energy from the solar photovoltaic system and from the EV (V2G operation mode) to the power grid. In this case it is used the ac-dc converter and both dc-dc converters. One of the dc-dc converters is used with a MPPT control algorithm to extract the maximum power form the solar photovoltaic system and the other is used with constant power control algorithm during the V2G operation mode. Figure 5 shows the power in the power grid side (P_{PG}) (cf. Figure 5(a)), the power in the EV (P_{EV}) (cf. Figure 5(b)) and the power in the solar photovoltaic system (P_{PV}) (cf. Figure 5(c)) during this case. As it can be seen, the power in the solar photovoltaic system changes according with the MPPT algorithm and the EV discharging power is maintained constant, while the power in the power grid changes according with the power of these two systems. In a third case the multifunctional

Table 1: Simulated Operation Cases to Establish the Estimated Operation Efficiency.

	Power Grid	Electric Vehicle	Solar PV Panels
Case 1	-3 kW	0 kW	-3 kW
Case 2	+2 kW	+5 kW	-3 kW
Case 3	-5 kW	-2 kW	-3 kW
Case 4	+5 kW	+5 kW	0 kW
Case 5	-5 kW	-5 kW	0 kW

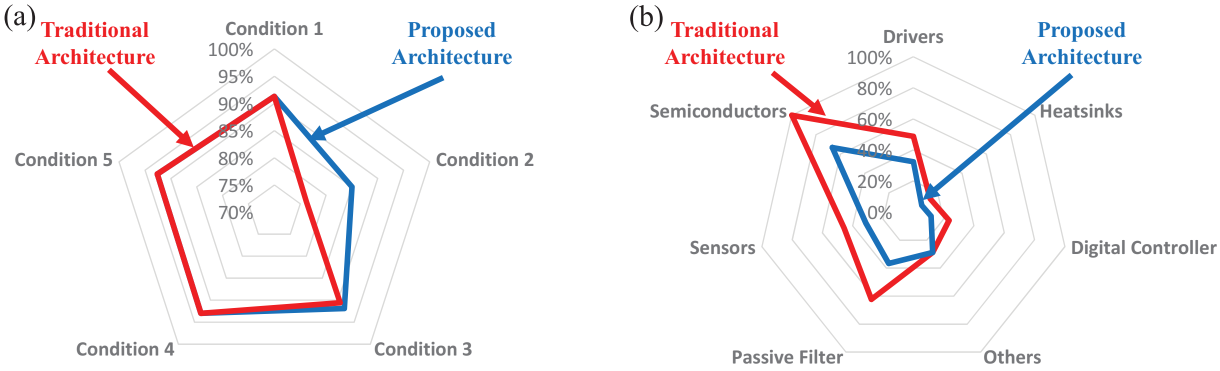

Figure 8: Comparative analysis between the traditional and the proposed solution in terms of: (a) Estimated operation efficiency: (b) Estimated cost of implemenmtation.

converter is used to inject energy from the solar photovoltaic system and to charge or discharge the EV batteries (G2V or V2G operation mode) to or from the power grid. In this case is used the ac-dc converter and both dc-dc back-end converters. Figure 6 shows the power in the power grid side (P_{PG})(cf. Figure 6(a)), the power in the EV (P_{EV}) (cf. Figure 6(b)) and the power in the solar photovoltaic system (P_{PV}) (cf. Figure 6(c)) during this case. As it can be seen, the power in the solar photovoltaic system changes according with the MPPT algorithm and the power in the EV batteries is measured in both G2V and V2G operation modes, while the power in the power grid changes according with the power in the solar photovoltaic system and with the EV operation mode. In a fourth case the multifunctional converter is only used to charge (G2V operation mode) or discharge (V2G operation mode) the EV batteries. In this case is used the ac-dc converter and a dc-dc converter during the G2V operation mode or during the V2G operation mode. Figure 7 shows the power in the power grid side (P_{PG}) (cf. Figure 7(a)), the power in the EV (P_{EV}) (cf. Figure 7(b)) and the power in the solar photovoltaic system (P_{PV}) (cf. Figure 7(c)) during this case. As it can be seen, these results were obtained in both G2V and V2G operation modes. As expected, the power in the power grid changes according with the power in the EV.

In order to analyses the viability of the proposed converter it was established a comparative analysis between the traditional and the proposed solution in terms of estimated operation efficiency and estimated cost of implementation. The comparison of the estimated operation efficiency was performed using the thermal module of the software PSIM, where it is considered the dynamic behavior of real semiconductors towards estimating switching and conduction losses. This comparison was established for the five operation cases summarized in Table 1 (The signal plus means that the power grid provides energy and the signal minus means that the power grid receives energy). Case 1: The power grid receives energy only from the solar photovoltaic panels (3 kW). Case 2: The power grid (2 kW) and the solar photovoltaic panels (3 kW) provides energy and the EV receives energy (5 kW). Case 3: The power grid receives energy (5 kW) from the solar photovoltaic panels (3 kW) and from the EV (2 kW). Case 4: The power grid provides energy to the EV (5 kW). Case 5: The power grid receives energy from the EV (5 kW).

Figure 8(a) shows the estimated operation efficiency for the five operation casess aforementioned. It can be observed that the efficiency is equal when the solar photovoltaic panels and the EV are operating individually. When both (solar photovoltaic panels and EV) are operating together the estimated efficiency is better with the proposed architecture. In the case 2 the estimated efficiency is improved 8.8% and in case 3 the estimated efficiency is improved 1.3%. Figure 8(b) shows a comparison between the traditional and the proposed architecture in terms of estimated cost of implementation. As it can be seen, the proposed architecture is cheaper in all the considered parameters. Globally, the cost of implementation is cheaper about 33.5% with the proposed architecture.

CONCLUSION

This paper proposes a multifunctional converter that is used to interface solar photovoltaic panels and electric vehicles (EVs) with the power grid in smart grids context, i.e., this converter is used to deliver energy from solar photovoltaic panels to an EV or to the power grid, and also to exchange energy in bidirectional mode between the EV and the power grid. Taking into account that it does not require multiple conversion stages, it is possible to define operation strategies and control algorithms in order to increase the global energy efficiency of the system without neglecting the power quality. Along the paper are presented and described the system architecture and the control algorithm, and are presented simulation results for the four distinct operation cases: (a) Transferring energy from the solar photovoltaic system to the power grid; (b) Transferring energy from the solar photovoltaic system and from the EV to the power grid; (c) Transferring energy from the solar photovoltaic system to the EV or power grid; (d) Transferring energy between the EV and the power grid. In comparison with the traditional architecture, the proposed multifunctional converter presents a maximum improved estimated efficiency 8.8% higher, and a total cost 33.5% lower.

ACKNOWLEDGMENT

This work has been supported by FCT – Fundação para a Ciência e Tecnologia in the scope of project: Pest-UID/CEC/00319/2013. Mr. Vítor Monteiro was supported by the doctoral scholarship SFRH/BD/80155/2011 granted by the FCT agency.

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