Bidirectional Charging System for Electric Vehicle with Improved Power Quality

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Alen Godson M D
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
alengodson@gmail.com

Favaz
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
favazabdulrasheed0@gmail.com

Ashnil T K
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
ashniltk2001@gmail.com

Muhammed Shameem M
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
shameemputhiyedath@gmail.com

Akhil Chacko
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
akhilchackoeee@gmail.com

Sooraj Suresh Kumar
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
sooraj1173@gmail.com

Jayaprakash P
Department Of EEE
Government College of Engineering
Kannur, Kerala, India
jayaprakashpee@gcek.ac.in

***Abstract*— Electric vehicle (EV) connected to the electric grid can not only recharge its own battery but can also feed energy back into the grid referred to as vehicle-to-grid (V2G). This technique helps to reduce peak load, regulating voltage, balancing of the load and increase the stability of power system. In this paper a battery electric vehicle (BEV) was utilized for both charging and discharging power. Bidirectional power transfer is accomplished through a bidirectional DC-DC converter and a single-phase full bridge inverter. This topology can minimize the harmonic distortion of the grid-injected current and keep it within standards. The control method proposed in this paper provides the user with the flexibility to select the operational mode of the circuit. Simulation of this system is verified in MATLAB Simulink.**

Keywords—Vehicle to grid, Grid to vehicle, Adaptive quadrature signal generator, State of charge

I. Introduction

Electric vehicles, or EVs, have a history that dates back to the late 1800s. They were quite popular and had decent sales until around 1918. However, as advancements in gasoline powered internal combustion engines (ICE) progressed, the utilization of EVs in transportation saw a decline. But worries about global warming, coupled with progress in car technology, have fueled the growth of electric vehicles. In the initial six months of 2023, there was a 40% increase in worldwide EV sales compared to the same period in the previous year. It is estimated that by the year 2030, electric vehicles will constitute between 35% and 40% of all new car purchases [1]. Major automakers are anticipated to produce over 70% of global EVs by 2030, a significant increase from 2022 when they only represented 10% of EV manufacturers. In [2], a comprehensive study is discussed that focuses on electric vehicles and hybrid vehicles, particularly on their motors and control drives.

Several factors contributed to the uptick in electric car registrations. Electric cars are becoming increasingly competitive in terms of total ownership costs in certain countries. Their increasing popularity today can be attributed to their cost-effective operation and superior efficiency [3]. Additionally, many governments have offered or extended fiscal incentives to encourage electric car purchases, helping to offset declines in traditional car markets.

The advent of EVs, capable of supplying power from their batteries to the grid, has led to the inception of the V2G concept. This transformative V2G technology has surfaced as a significant breakthrough in the automotive and energy industries, facilitating a two-way energy transfer between EVs and the grid [4]. This transformative technology allows EVs to not only consume electricity but also to store and supply energy back to the grid, creating opportunities for grid stabilization, demand response, and renewable energy integration. The V2G technology in electric vehicles contributes to grid stability by providing power during high demand periods and recharging during low demand periods. The V2G idea has the potential to enhance the efficiency, stability, and dependability of the power grid. An EV can function as an energy backup for a home, charging during periods of low demand or soaking up surplus energy from renewable energy resources (RES), like a residential wind turbine or solar panel system. This way, it contributes to a more sustainable and efficient energy ecosystem [5]. Furthermore, a vehicle equipped with V2G capabilities can provide support for reactive power, regulate active power, track changes in renewable energy sources, balance loads, and filter current harmonics. This enhances the overall efficiency and stability of the energy system. V2G technology has the potential to change how we generate and use energy, but there are obstacles to overcome. These include the lack of standard rules for communication between V2G systems and the power grid, the high cost of bidirectional chargers, uncertain regulations, safety worries, and the limited availability of EVs compatible with bidirectional charging. Despite these challenges, ongoing trials worldwide aim to find solutions and unleash the potential of V2G technology, which could greatly improve energy grids and help us shift to renewable power sources completely.

In the era of battery chargers for EVs, various power converter topologies are explored in literature, including AC-DC and DC-DC converters like buck, boost, buck-boost, flyback, forward, cuk, sepic, and zeta [6]. However, due to their one-way operation, these converters aren't suitable for V2G applications. To address this, bidirectional converters are needed. In [7] presents the development of a bidirectional power converter for grid-to-vehicle (G2V) charging and V2G energy return. The converter maintains grid power quality by consuming sinusoidal current with controlled power factor.

Efficient control algorithms and passive filters are integral for bidirectional power flow. The paper [8] explores a variety of control strategies, including multi-agent control (MAC), aggregated control, and load frequency control, for the purpose of integrating EVs into the power system. Validation involves computer simulations followed by experimental tests with a prototype to ensure proper functionality and performance. In [9] outlines all the primary operational modes of an EV battery charger within smart grids and smart homes, focusing specifically on V2G and G2V operation modes. It presents a basic architecture of an EV charging system, which can be divided into two parts: one for controlling the DC-DC converter and another for the AC-DC converter. The DC-DC converter injects a desired current, followed by the AC-DC converter which counteracts any undesirable changes made by the DC-DC converter on the DC link. Each control algorithm regulates its respective converter by generating PWM signals for their switches. In [10], a versatile control system is detailed for a solar photovoltaic integrated battery energy storage system (PVBES), capable of operating in both grid-connected mode (GCM) and standalone mode (SAM). In grid-connected applications, phase-locked loops (PLLs) emerge as the foremost technique for synchronizing power electronics-based converters [11]. Among these, quadrature signal generation-based phase-locked loops (QSG-PLLs) are widely favored.

In this paper, a bidirectional charger facilitating a bidirectional power flow is presented. A modified adaptive quadrature signal generator (AQSG) control is employed for grid connection with superior power quality method. The topology and control techniques are explained in the following sections. Further, simulation of the system using MATLAB/Simulink has been presented.

II. BIDIRECTIONAL CHARGER TOPOLOGY

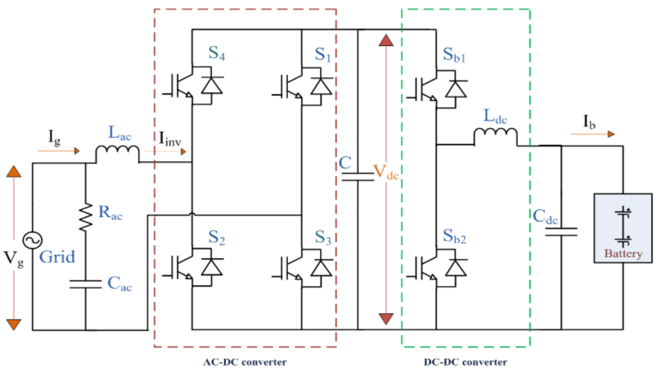

Fig. 1. Bidirectional charger

The presented topology comprises a battery, a DC-DC converter, an AC-DC converter utilizing a single-phase full bridge configuration, and passive filters. The presented topology facilitates both buck and boost operations. Similarly, AC-DC converter facilitates both inverting and rectifying operation, enabling bidirectional power flow. The interfacing inductor ($L_{ac.}$) reduce harmonics in inverter current to feed the grid. While RC filter parallel to the grid reduce harmonics in source voltage. Fig. 1 shows the circuit diagram of the bidirectional charger.

III. CONTROL STRATEGY

Whole system is working according to three conditions as illustrated in fig. 2. Most significant among them is the user selection. User selection varies the state of an input digital signal 'M'. If M=1 the V2G mode will comes on operation and when M=0 the G2V mode will operate. Other conditions are state of charge (SoC) of the battery and power demand at the grid. The V2G won't be activated with a battery of low SoC or grid with low power demand (electricity price in $/unit). The information is elaborated with greater specificity in fig. 3. Although the system will operate in G2V mode initially before transitioning to the desired mode for achieving grid synchronization. Control method for each part is discussed thoroughly below.

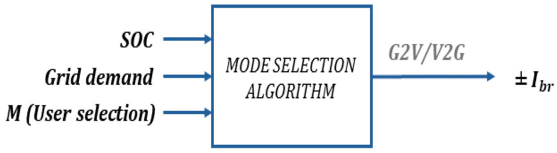

Fig. 2. Block diagram for mode selection

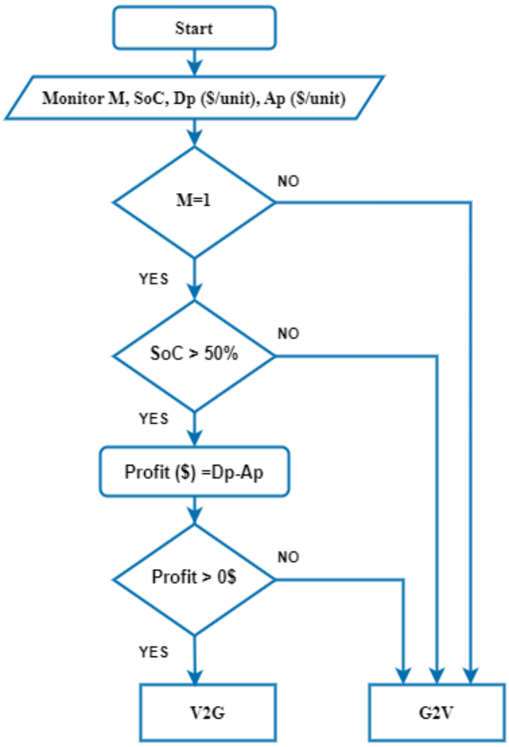

Fig. 3. Mode selection algorithm

Where :

Ap	:	Average electricity price ($/unit)
Dp	:	Dynamic electricity price ($/unit)

A. Current control of DC-DC converter

The DC-DC converter within the circuit is made closed loop in constant current mode initiating the power flow in the circuit. Fig. 4 presents a comprehensive block diagram illustrating the control procedure employed. The battery current (I_b) is compared with a desired reference current ($I_{br.}$). PWM signals for the switches are produced based on their respective errors. The target reference current is subjected to variation in accordance with the input signal 'M' and other conditions specified.

B. Generation of reference grid current

The voltage of DC link (V_{dc}) will vary according to the current injected by DC-DC converter. The DC link voltage have to be kept as desired. The AC-DC converter control is designed to balance the voltage change and keep the DC link voltage as desired. Hence, the AC-DC converter should draw a current from the grid to maintain the DC link voltage as desired. The magnitude of reference grid current has to be estimated to set the DC link voltage as desired. Hence for the estimation, DC link voltage is compared with a reference voltage, and the error is passed to PI controller for the estimation of magnitude of reference DC link current (I_{gdc}).

A battery reference current (I_{gb}) is calculated to regulate the magnitude of grid current to enable V2G or G2V operation. For that the battery reference power is calculated as

$$P_b = I_{br} V_b \tag{1}$$

From the battery power the peak of the grid current (I_{gb}) needed for V2G or G2V is calculated. The sum of I_{gb} and I_{gdc} will give the peak value of reference grid current (I_{gpr}).

To accurately estimate the grid current, so that it matches the grid voltage waveform in terms of phase angle and frequency, the unit template of the grid voltage must be calculated. An AQSG model is used for calculating the in-phase and quadrature-phase fundamental components of the grid voltage waveform. The driving equations of the AQSG model are given below [10].

$$V_\alpha(s) = \frac{1}{s}\{T_a\,[V_t(s) - \alpha(s)] - \omega_0 V_\beta(s)\} \tag{2}$$

$$V_\beta(s) = \frac{1}{s}\, T_a[-V_\beta(s) + \omega_0 V_\alpha(s)] \tag{3}$$

Where V_α and V_β are the in-phase and quadrature-phase voltages, V_t is the fundamental component of grid voltage. From the obtained data, amplitude of the signals and their unit templates are estimated. The equations required for the calculation are given below [10].

$$V_t = \sqrt{(V\alpha^2 + V\beta^2)} \tag{4}$$

$$U_p = \frac{V\alpha}{Vt} \qquad U_q = \frac{V\beta}{Vt} \tag{5}$$

Where V_t is the terminal voltage. V_α and V_β are in-phase and quadrature phase signals of the grid voltage.

Product of estimated in-phase unit template and estimated current magnitude gives desired reference grid current. Hence reference grid current is generated.

C. Grid current control

Like DC-DC converter current control, the current from grid is compared with estimated reference grid current and PWM pulses are generated using the hysteresis controller according to the error between the currents. The system hence tries to generate an output similar to the reference. These PWM signals are given to the inverter switches. Fig. 4 depicts this procedure.

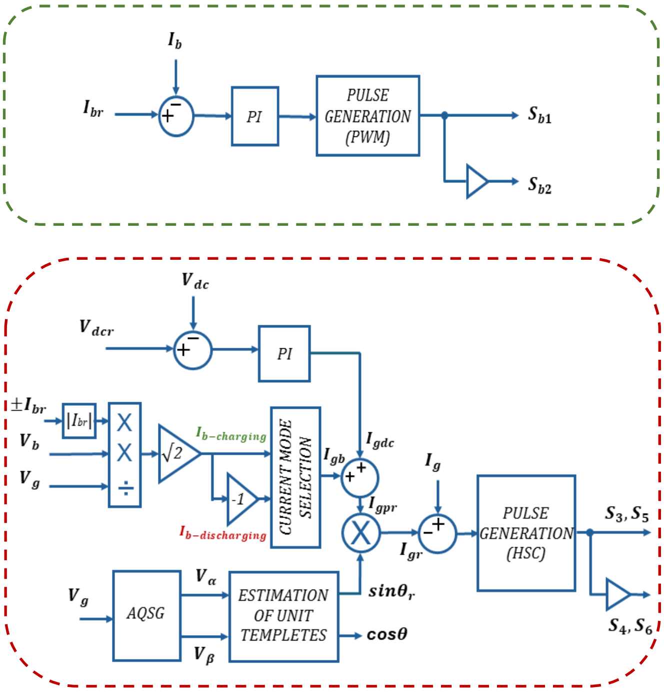

Fig. 4. Block diagram of the modified AQSG control for power flow of bidirectional charger

IV. Results and Discussion

The bidirectional charging system for EV has been implemented in MATLAB-Simulink. In the simulation, the Lithium-ion battery has 100 Ah. A single phase 230 V, 50 Hz supply is chosen as grid. The simulation results for both the V2G and the G2V operations are provided. Table.1 shows the simulation parameters for the bidirectional charger.

Table I. Simulation parameters

Sl. No	Parameter	Value
1	Lithium-ion battery	260 V
2	Inductor L_{dc}	10 mH
3	Capacitor C_{dc}	1000 µF
4	DC-link capacitor C	2200 µF
5	Interfacing inductor L_{ac}	4 mH
6	Grid voltage	230 V
7	Grid frequency	50 Hz

A. V2G mode

In V2G mode a battery discharge current of 10 A is chosen and the system is made is simulated. The current and voltage waveforms at grid side during V2G mode and corresponding inverter current and DC link voltage have been shown in fig. 5, whereas the THD of grid current is displayed in fig. 6. While the Fig. 7 shows the voltage, current and SoC of the battery. The voltage of DC link is found to be same throughout the Working but at 400 V. The SoC is found is decreasing successfully. A grid current THD of 2.52% is obtained.

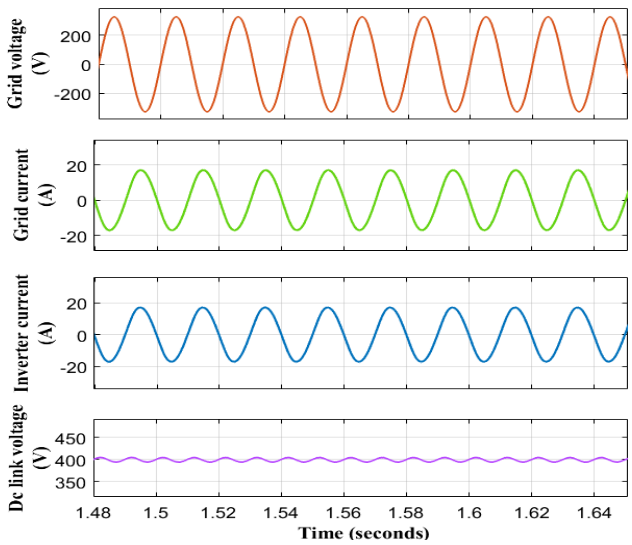

Fig. 5. Grid voltage, grid current, inverter current & DC link in V2G

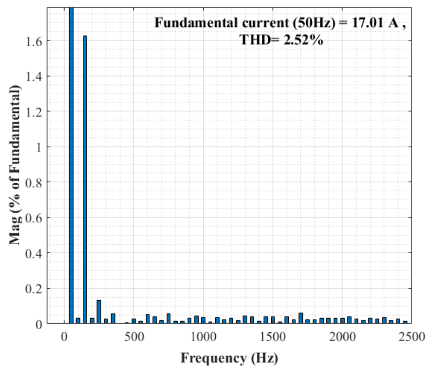

Fig. 6. THD values of grid current in V2G mode

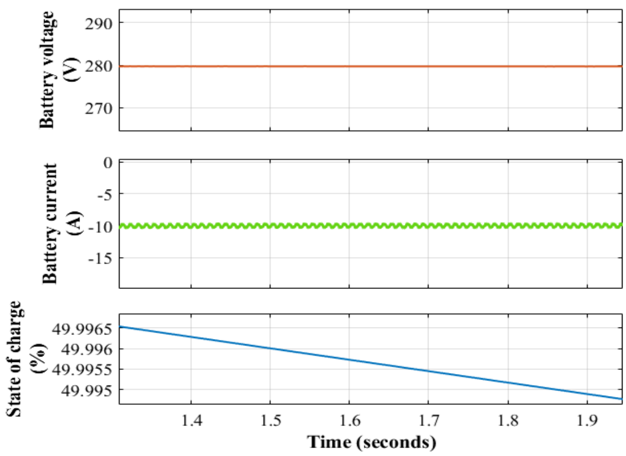

Fig. 7. Battery parameters in V2G mode

The dynamic response during V2G was verified. For that, the battery is initially operated to discharge a current of 10 A and then suddenly the battery is made to discharge 5 A. Fig. 8, fig. 9, demonstrates the system performance during this dynamic condition. There are no significant changes in the DC link voltage and grid voltage during the condition. There is a fall in grid current due to the fall in battery discharge current. The power quality is maintained during the dynamic condition.

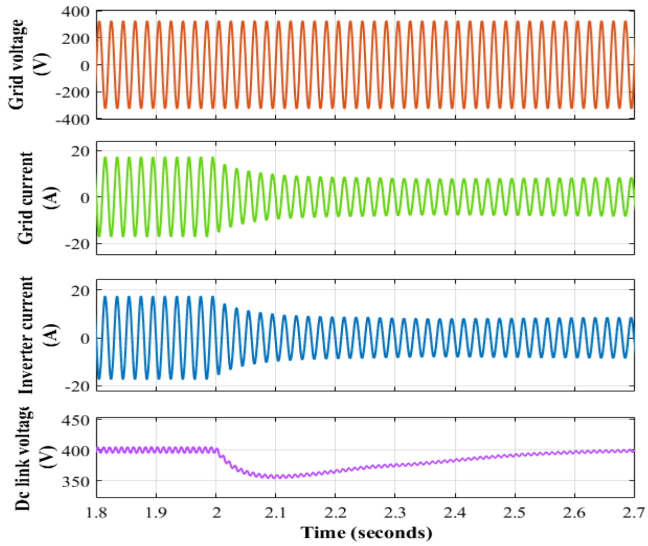

Fig. 8. Dynamic response of V2G mode

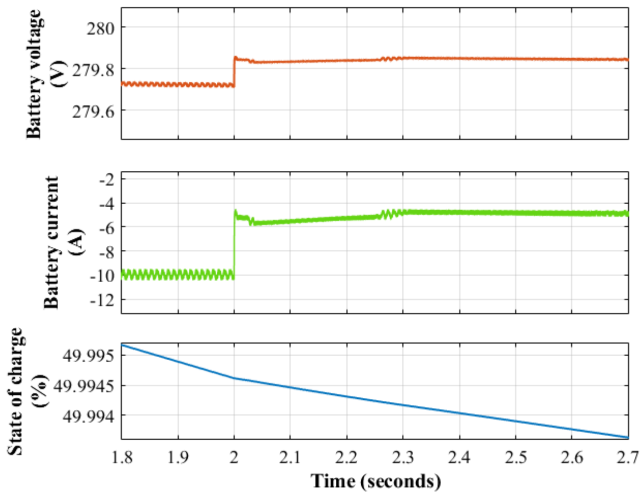

Fig. 9. Dynamic response of battery parameters in V2G mode

B. G2V mode

In G2V operation mode, the battery charges with a current of 10 A and the results are observed. The current and voltage waveforms at grid side, DC link voltage and inverter current have been shown in fig. 10. The THD of current in grid is displayed in fig. 11. Fig. 12 shows the voltage, current and SoC of the battery. The DC link voltage is found to be unchanged throughout the working at 400 V. The SoC is found to be increasing demonstrating that the battery is getting charged. The observed THD of grid current is 2.48%.

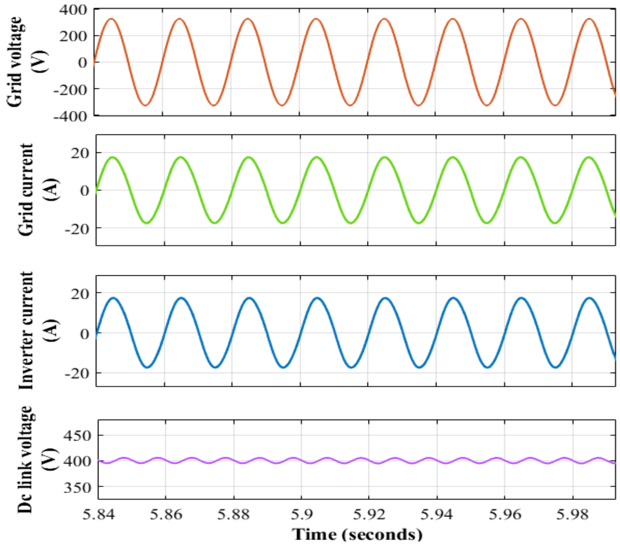

Fig. 10. Grid voltage, grid current, inverter current & DC link in G2V

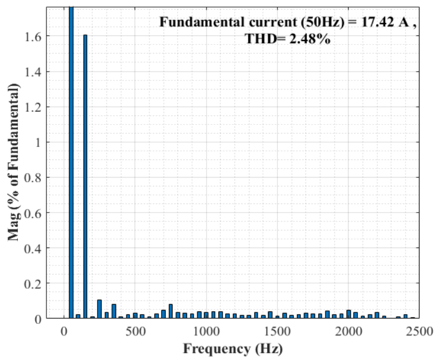

Fig. 11. THD values of grid current in G2V mode

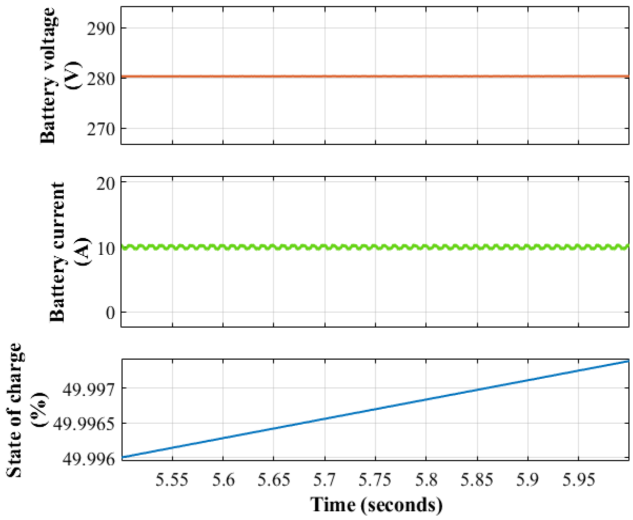

Fig. 12. Battery parameters in G2V mode

V. Conclusion

The simulation of a bidirectional charger for a grid connected, EV has been presented in this paper. The modified AQSG based control used in this work enables bidirectional power flow with proper control and maintains the power quality of the grid within standards. The THD of the grid voltage and grid current are maintained within IEEE 519 standards by the modified AQSG control. Also, the power factor of the system is maintained at UPF in both V2G and G2V mode of operation, by this control.

Further this control can be extended to provide power to a local load in either a grid connected or islanded mode of operation, enabling the EV to provide interrupted power to a connected household.

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