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DC-DC CONVERTER SOLUTIONS FOR MODERN ELECTRIC VEHICLE POWER SUPPLY SYSTEMS

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***Abstract* –The main objective of this paper is to present a survey on power electronics DC-DC converter arrangements and basic cell structures that are used to combine multiple and different power sources with distinct energy and power density. The power electronic converter must be able to control the power flow among the multiple power sources and loads. An important feature of this converter, in applications such as modern electric vehicles and distributed generation supply systems, is to obtain high individual power sources performance, achieving high efficiency in the use of the generated power and improving the time response under load disturbances. In fact, the control strategy of the overall power electronic converter system is quite challenging because the vehicle performance must also be considered. An energy management fuzzy supervisory system witch takes into account all these issues are presented. Experimental results on a 3 kW prototype multiple input power electronic converter are presented.**

***Keywords* – road electric vehicle, supercapacitor, fuel cell, multiple input power electronic converter, DC-DC converter and energy management.**

I. INTRODUCTION

The integration of different power sources with distinct energy and power density enables the coordination of the advantages of each source and overcome the limitations they may have. This issue is crucial in order to increase the durability, the reliability and the efficiency of the power sources.

The Ragone Diagram, shown in Fig. 1, is a chart that compares the performance of energy storage and conversion devices in terms of power and energy density [1] – [2]. According to the Ragone Diagram, it is possible to think that the fuel cell (FC) could replace the batteries (BTs) to drive a modern electric vehicle (EV) due to the weight and volume reduction.

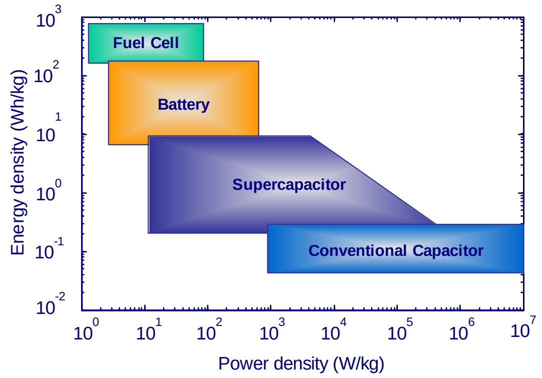

Fig. 1. Ragone diagram: energy and power density.

The biggest amount of energy available from FC can raise the vehicle autonomy. However, the FC presents low efficiency at low power demand, slow power transfer rate in transient situations and high cost per Watt. It is clear that some other source should be used to allow faster power delivery to the traction system. As a result, it is not necessary to size the FC to the peak power demand, but only to the average power. In addition, this procedure increases the FC lifetime.

It is known that batteries have the required power capability necessary to drive urban light EV. They are able to supply additional power, which is necessary during long (seconds to minutes) acceleration periods. However, fast current variations produce considerable power losses and may reduce their lifetime [3] – [4].

For batteries and fuel cells, the chemical to electrical energy conversion depends on a slow electrochemical process. Thus, a usual solution employs also a supercapacitor (SC) bank to improve the time response supply system under sudden load disturbances.

The Fig. 2 shows a schematic general-purpose structure DC-DC converter used to interface the supply system (fuel cell, battery and supercapacitor) with the traction system of an Electric Vehicle. The Energy Management System controls the power converter based on the power source characteristics and the load demand, that comprise propulsion (traction motor) and non-propulsion (lamps, for example) loads. It is clear that the system can use other power sources. For example, an internal combustion engine with an electric generator can replace the fuel cell generator.

There are several arrangements and topologies proposed to combine different power supplies, in which it is possible to accomplish the active control of one or more supply devices [5] – [9]. In general, the independent power source control requires a large number of electronic components and needs more sophisticated energy management strategies.

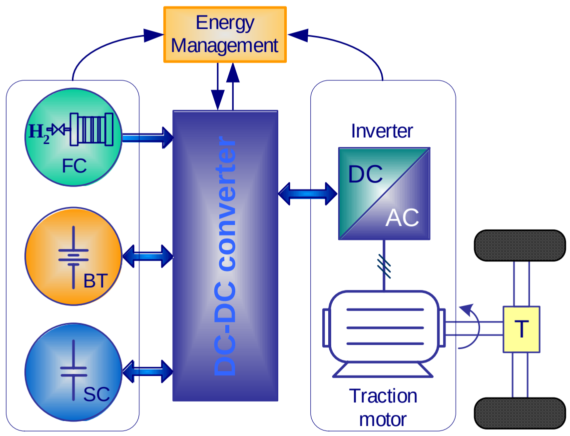

Fig. 2. Schematic structure of an electric vehicle propulsion system.

The main challenges of choosing a power converter are the following: low cost acquisition and maintenance, compact size, reliability, small electromagnetic interference, low acoustic noise and high efficiency.

Based on a general power source combination, a family of power electronics DC-DC converter arrangements and basic cell structures are presented in this paper. The potential applications of these power electronic converters include modern electric vehicles and distributed generation systems.

The experimental results from a 3 kW multiple input power electronic converter is presented at end of this paper.

II. POWER SOURCE ARRANGEMENTS

The effect of current peaks on BT and FC is accumulative and harmful. It can be associated to power losses, temperature increase and lifetime reduction of these devices.

The classical solution to dampen the fast current variations on the primary power source (FC) is the association with a larger power density source. Several applications use the battery in spite of its performance degradation over time.

The supercapacitor modules are the most viable technology to protect the power supply system from sudden power demands [10]. However, it is necessary to define adequately the power converter arrangement in order to get high efficiency and good allocation from each power sources available resources.

The direct connection of the SC to the BT terminals, or FC, limits a wider use of SC as power source [11]. In this arrangement, the SC (due to its low internal resistance) works only as a current filter, avoiding a very high voltage drop in BT terminals.

For simplicity and better comprehension, some examples of power arrangements for applications that use two power sources are presented bellow. The BT is used as primary source and the SC is used as the power source. The arrangements are also valid if the BT is replaced by a FC and the BT replaces the SC.

It is important to highlight that the arrangements can also be used if three sources are considered (FC, BT and SC).

A. Series Connection

Fig. 3 shows the series connection arrangement in which the primary source (BT) is connected in series with the SC [6]. The benefits of this arrangement are the use of a SC module with lower voltage rate and a DC-DC converter with smaller power rate than other solutions.

The DC-DC converter is used to recharge the SC, especially during regenerative braking. In other words, it works only like a step-down converter. This configuration limits the potential use of SC during motoring operation and the primary source can be affected by sudden load demand.

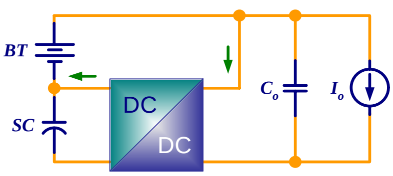

Fig. 3. Series connection arrangement.

An important issue that has not been described by the authors in [6] is the fact that if a bidirectional DC-DC is used, a better DC output voltage regulation can be achieved. Thus, the SC can transfer energy quickly to load, by the DC-DC bidirectional converter, which would reduce the maximum load demand from primary source.

The SC's minimum voltage could be limited by the converter performance (static gain). On the other hand, the maximum SC current is restricted by power transistors rate because the SC current limit is too high.

B. Cascade connection

The Fig.4 shows the cascade connection arrangement, where the current of the primary source is actively controlled by means of a DC-DC converter control [6], [11] – [14]. The SC is directly connected to the DC output bus.

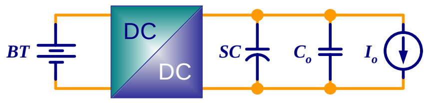

Fig. 4. Cascade connection arrangement.

This arrangement allows the primary source to supply the average power demand, while the SC reduces the peak power demand. The main drawback of this configuration is the employment of a high voltage SC module.

It is also possible to invert the position of the primary source and SC, where the DC/DC converter must be bidirectional in current to allow SC recharge. However, SC's dynamic behavior is limited by current converter capacity and the primary source can still be subjected to fast current variations, of smaller intensity although. In addition, the output voltage may present poorer regulation than the previous solution due to the slow time response of primary source.

A more attractive option is to include an additional DC-DC conversion stage between the power source and load, as shown in Fig. 5 [15]. This configuration increases the controllability of the overall system, the primary power source is not so affected by sudden load demands and the SC voltage can change the voltage in a wide band level.

The drawbacks of this arrangement are: the converter that is next to the output voltage bus must process all the power that is required by the load; and the power generated by primary source is processed two times, which means that this arrangement may be less efficient than the counterparts.

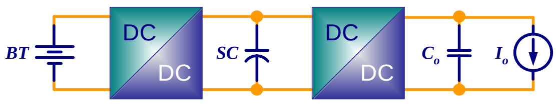

Fig. 5. Two stages cascade connection arrangement.

C. Parallel connection

Fig. 6 shows the parallel connection arrangement, in which the power sources are connected in parallel through DC-DC converters [5], [16] – [17]. In this arrangement, unlike the cascade arrangement (Fig. 5), the converters only process the power of the source that they are connected to. However, this connection requires a more complex control strategy to coordinate the power flow among the power sources.

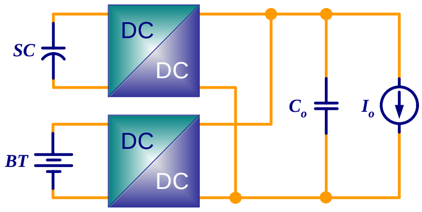

Fig. 6. Parallel connection arrangement.

D. Other connection types

Fig. 7 shows the power converter arrangement proposed by Marchesoni and Vacca that uses only three switches to implement the active control of the power sources [18] – [19]. The switches commands are too complex. One of the switches is turned-off while the other two are turned-on. This topology implements two bidirectional boost converters that enable the recharge of storage energy devices.

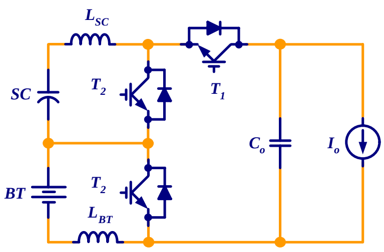

Fig. 7. Arrangement proposed by Marchesoni and Vacca.

Using three power sources (FC, BT and SC) it is possible to mix the arrangements previously showed. It is important to point out that the best arrangement selection depends on voltage source rate and converter characteristics.

III. BASIC TOPOLOGIES OF DC-DC CONVERTERS

Based on fuel cell, battery and supercapacitor operations characteristics and electric vehicle applications, this section presents the basic DC-DC topologies that can be used to implement the power source arrangements previously presented.

Typically, DC output bus voltage must be high, around 300 V, due to high power required by traction mechanism [8], [20]. Thus, the DC-DC converters must contain a step-up voltage characteristic.

In addition, energy storage devices require bidirectional topology to allow the recharge, while the DC generator (fuel cell, in this case) needs only a unidirectional topology.

A. Non-isolated and unidirectional

The basic unidirectional and non-isolated DC-DC converter topologies that allow to step-up the output voltage are: boost, buck-boost, Ćuk, SEPIC and Zeta converters [21].

The Zeta and buck-boost converters are not adequate, because they present pulsed input current (i. e., high current ripple), which is potentially harmful to fuel cell and battery. For the same reason, the discontinuous conduction mode is not allowed.

Ćuk, SEPIC and Zeta converters have a larger number of passive elements than the boost converter and the fourth order dynamic behavior, which increases the modeling and design controllers complexity. The switches from these converters are submitted to a voltage that is the sum of input and output voltage, and the current is the sum of the input and output current. In comparison to the SEPIC converter, the Ćuk converter presents a natural output current filter however the output voltage polarity is inverted.

As a consequence, the most appropriated solution for conditioning the power generated by a fuel cell is a boost converter, which is traditionally used on fuel cell commercial systems.

B. Non-isolated and bidirectional

The basic bidirectional and non-isolated DC-DC converter topologies are usually used to drive DC motors. The Fig. 8 shows the chopper topology, V_i and I_o are the power source and the propulsion load respectively [16], [21]. One advantage of this topology is the commercial availability of the converter. In addition, the inductor, series connected to the power source, limits the current ripple, which is an interesting characteristic for battery use.

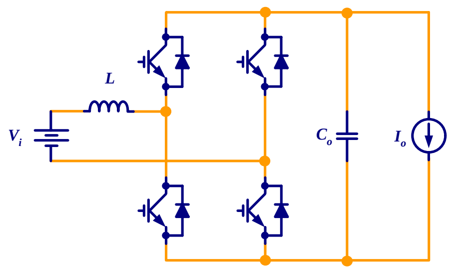

Fig. 8. Chopper converter topology.

In terms of storage devices (BT and SC) protection and converter cost, the bidirectional boost converter topology, shown in Fig. 9, is more appropriate than the chopper converter [9], [22]. It requires fewer switches and it does not allow voltage reversibility. From the output point of view, the converter acts like a boost converter, while from the input point of view the converter acts like a buck converter.

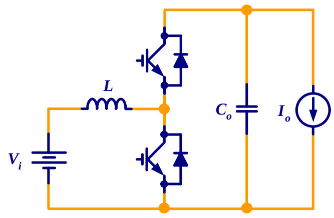

Fig. 9. Bidirectional boost converter topology.

Usually, the switching commands of the top and bottom transistors are complementary pulses. This procedure has two advantages: guarantees that the converter always operates in the continuous conduction mode and allows a continuous transition when the current is inverted.

A capacitor can be connected at the power source terminals in order to minimize the circulation of current ripple [23]. A “T” filter (additional inductor series connected between the power source and input capacitor) may be an interesting solution to reduce the capacitor inrush current [24].

C. Isolated and bidirectional

Despite being more attractive for Distributed Generation and UPS systems, the isolated DC-DC converters are especially interesting for applications in Electric Vehicles when high voltage gain is required. In addition, they present a natural over-current protection and flexibility to combine power sources with different voltage level.

Fig. 10 shows the full-bridge and half-bridge converter topologies. However, these converters have high current ripple, and are most appropriate to be used on the secondary transform side, i. e., at the load side [5].

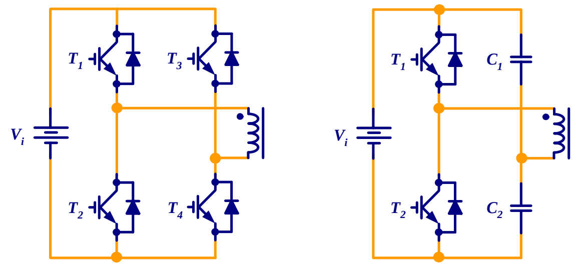

Fig. 10. Full-bridge (left) and half-bridge (right) converter topology.

Fig. 11 shows the boost half-bridge converter, in which the capacitors C_1 and C_2 act like the filter from boost topology and also as a capacitor divider from half-bridge topology [5], [25]. The power flow between the power source and the load is controlled by shifting the primary and the secondary transistors command signals. The main advantages are: galvanic isolation, soft switching (without additional resonant circuits) and low current ripple.

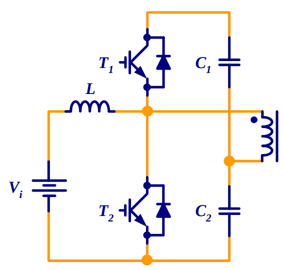

Fig. 11. Boost half-bridge converter.

D. Interleaved converter

For high power applications, it is necessary to take into account the problems related to magnetic components design. The typical solution is the employment of interleaved strategies, which enables working with high source currents and reduced filter requirements [26].

The Fig. 12 shows the schematic circuit of a three-phase interleaved bidirectional boost converter. The inductors current are interleaved by delaying the PWM signals to the switches [27]. It is clear that this solution can be used for isolated converters too.

IV. MIPEC

A family of multiple input power electronics converter (MIPEC), using multiple energy sources, can be built from the converters arrangements and the basic cell structures presented. The best power converter solution depends on the operation characteristics of the source devices.

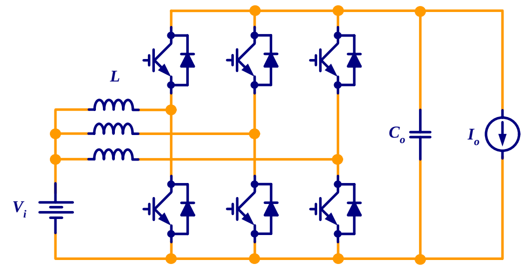

Fig. 12. Three-phase interleaved bidirectional boost converter.

The fig. 13 shows a MIPEC isolated topology [28]. The converter combines parallel arrangement and magnetic coupling. This arrangement is more attractive for applications where the voltage level from power sources is too low and the load voltage is high. However, if SC module voltage is medium, the cascade connection (showed in the Fig. 5) implemented with a non-isolated converter topology could replace this circuit, the conversion efficiency needs to be evaluated though.

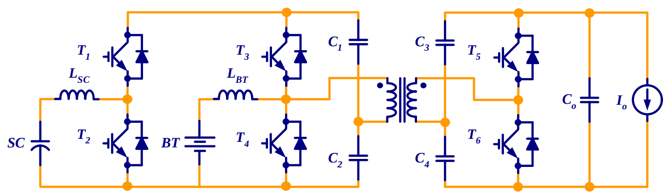

Fig. 13. MIPEC isolated and parallel topology.

The fig. 14 shows a MIPEC non-isolated topology, which is based on the parallel arrangement (see Fig. 6) that connects three power sources to the traction system [9]. This topology is essentially a set of bidirectional boost converters sharing a common output capacitor. Each DC-DC converter is built using a phase lag from a commercial three-phase inverter, in which the top transistor from fuel cell circuit is always turned-off because the FC can not regenerate energy.

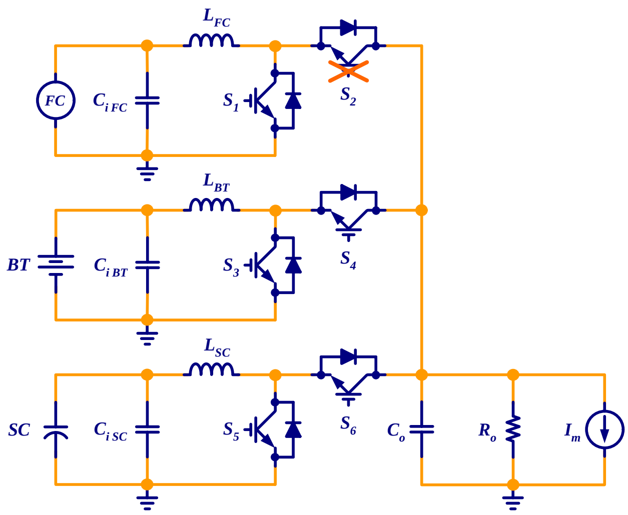

Fig. 14. MIPEC non-isolated and parallel topology.

The capacitor connected at each power source terminals minimizes high-frequency current circulation components through the power sources. This filtering is effective due to the source's inherent series resistances.

V. ENERGY MANAGEMENT CONTROL STRATEGY

Several control strategies are proposed to achieve an adequate propulsion system performance for pure electric vehicles and hybrid electric vehicle (HEV) [11], [13] – [14], [17], [20], [29]. In general, optimization methods are used to find the maximum efficiency situation and/or the optimal system performance. The main challenge of these control strategies is to define the variables to be optimized while complying with specific constraints generally imposed by dynamic device features and power demand.

The control system of a multiple input power electronic converter configures a typical multiple-input single-output (MISO) control system. A good solution is the use of conventional PI controllers to control the power flow of each power source and a supervisory system to coordinate the dynamic resource allocation.

The Fig. 15 shows the schematic diagram of an Energy Management Fuzzy Logic Supervisory System [30] designed to achieve the high-efficiency operation region of the individual power source and to regulate current and voltage at peak and average power demand.

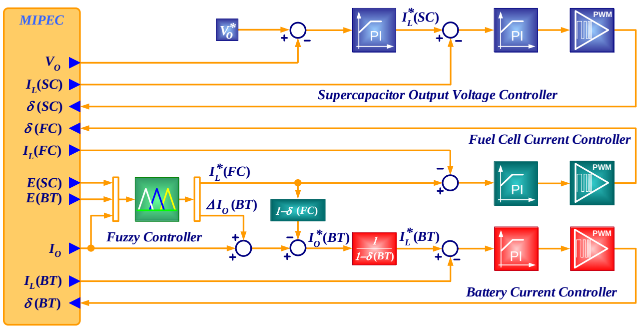

Fig. 15. Energy Management Fuzzy Logic Supervisory System.

The FC and BT linear compensators control the input current of each corresponding power source. The SC is responsible for the regulation of the DC-link voltage due to its high power density. Hence, the DC-link voltage control strategy does not depend on the fuzzy logic controller, and uses a classical inner current and an outer voltage control loop.

The FC is set only at two different operating points instead of varying continuously. The operating point related to the minimum power is chosen considering the constraint of maintaining the FC temperature, while the operating point corresponding to the maximum power is related to the average load power demand. The BT reference current is obtained by calculating the complement of the FC current to assure the required load current. A correction factor (ΔI_o) changes the BT reference to control the stored energy level of the SC. Despite not shown in the block diagram, a slope limit is used in the BT and FC commands to avoid fast current variations. The slope limits are +10 A/s and -25 A/s for the FC, and +25 A/s and –50 A/s for the BT.

Among the several Energy Management control strategies that were proposed in the literature, the Fuzzy Logic is an interesting tool to work with nonlinearities and restrictions from power sources and overcome the difficult to obtain the model of interactions among power sources on the parallel topology. The Fuzzy controller does not guarantee optimal results in all situations, but provides a satisfactory solution to control the SC energy state and to command the FC operation based on load demand and energy storage devices energy state.

VI. EXPERIMENTAL RESULT

The fig. 16 shows the experimental result from MIPEC system (Fig. 14) under sudden load disturbance, that is, due to resistive load connection. The SC quickly responds to load current increase transferring energy to keep the DC-link voltage constant, as shown on top graph, while BT current increases at a slower rate (+ 25 A/s). During this transient, the current supplied by the FC did not change because the energy state of the storage devices were in good conditions during the test. Note that, when the power demand decreased, the SC absorbed the power delivered by the batteries, and kept DC-link output voltage stable.

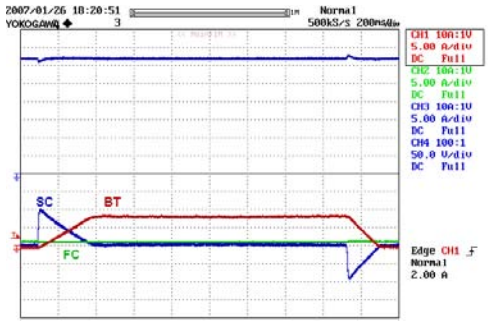

Fig. 16. Experimental result of MIPEC non-isolated and parallel topology in response to resistive load connection.

Thus, the storage elements provided the power during the entire time interval, while FC worked on minimum power mode. In addition, the output voltage controller was able to regulate the output voltage at 320 V by using the SC subconverter.

The fig. 17 shows the experimental result to drive an induction motor by using an industrial inverter. The driver takes 5 seconds to ramp the motor speed up to the desired value. Initially, the BT provides the power required by the load, without requesting additional power from the SC or FC. When the load demand is too high, the FC changes the operation for the maximum power mode. When the motor stops, the SC quickly absorbs the spare energy, keeping the DC output voltage constant. In addition, the SC smooth the voltage fluctuations caused by such pulsating current load characteristic.

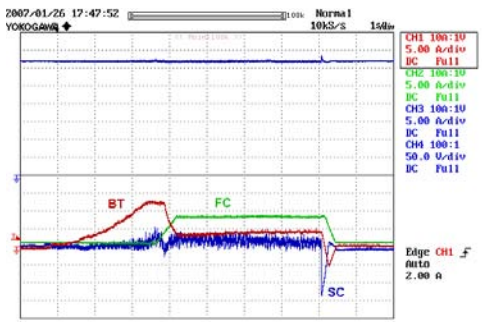

Fig. 17. Experimental result of MIPEC non-isolated and parallel topology in response to traction load.

VII. CONCLUSION

This paper has presented a survey on power source arrangements and basic topologies of DC-DC converters that are used to combine multiple and different power sources for electric vehicle applications. These structures can also be used for Distributed Generation and UPS systems, where the isolated converter topologies are probably more appropriate.

The most adequate power source arrangement and DC-DC converter solution to build a multiple input converter depends on power source and load operation characteristics, such as the necessary voltage gain and overall system efficiency.

A detailed model analysis and the static and the dynamic behavior from DC-DC converters are beyond the scope of this paper, but can be found in the references.

The power energy management strategy for a MIPEC non-isolated and parallel topology have been implemented in ADSP-21992, using a Fuzzy Logic controller and were tested on a 3 kW prototype to validate the desired performance of the electric vehicle supply system.

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