A Review of Single-Phase On-Board Integrated Battery Charging Topologies for Electric Vehicles

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***Abstract*–The paper provides an extensive overview of single-phase on-board integrated battery chargers for electric vehicles (EVs). Although commercial EVs are still to be equipped with integrated chargers, a multitude of topologies have been proposed for integration. Therefore, the need for classification arises. This paper aims to give an overview of topologies based on functionality of their integrated components. Moreover, it attempts to provide an extensive analysis of their operating principles. All the topologies are classified into three major groups. At first, topologies in which only the converter is integrated are considered. This is followed by configurations based on switched reluctance machines (SRM) in which both the converter and the machine are integrated. At last, the integration of both converter and induction machine (IM) or permanent magnet machine (PM) is elaborated within the third group. Here an example of obtained experimental results is also given. Finally, a short quantitative comparison of the topologies is provided in a table format.**

***Index Terms*–Integrated battery charger, on-board charger, electric vehicles, single-phase charging.**

I. Introduction

Recent fossil fuel shortage and global warming related problems have caused a substantial shift from internal combustion engine vehicles towards EVs. However, high battery price and slow charging process are still aggravating the change. At present, in nearly all commercial EVs, chargers are placed on-board as separate units. This to a large extent limits the charging power, since a charger rated for high powers would be too heavy to place on-board the vehicle. Moreover, it would also have a negative impact on the vehicle's weight, as well as on the required space under the bonnet.

One possible solution to this problem is reutilization of existing power-electronics components. Namely, power electronic components that are used for the propulsion and those required for battery charging purposes are never used simultaneously. Since these elements are similar to each other, it is possible to allow some of them to perform multiple functions. If the same drivetrain is utilized for propulsion as well as for the charging process, the charging power is no longer limited by its size, cost and weight, since the drivetrain is already required for the propulsion.

The idea of integration for the charging purposes is more than thirty years old. Many integrated topologies have appeared in this time span. Some of them are reviewed in [1-3], together with non-integrated chargers. Reviews of pure integrated solutions can be found in [4-7].

This paper focuses on single-phase integrated charging topologies. Although they are not capable of fast-charging the battery, they still present a great asset to every EV due to wide-spread existence of single-phase mains. Chargers are classified into three main groups based on the level of integration and the type of the motor that is used in the vehicle. A further classification in the paper is done by functions that integrated components have during the charging process. Analysis of operating principles of each group is provided as well.

The paper is organised as follows. In Section II topologies that integrate only the converter into the charging process are surveyed. In these topologies electrical machine is used only for propulsion purposes. Next two sections discuss topologies in which both a converter and a machine are integrated into the charging process. In Section III the machine type is SRM. Section IV reviews topologies employing the most common types of EV machines, which are IM and PM machines [8]. In this Section an example of obtained experimental results is presented as well. Finally, a short quantitative comparison of the topologies discussed in the paper is provided in Section V. Section VI concludes the paper.

II. Topologies Incorporating the Converter into the Charging Process

The first proposals for integrated chargers were mostly based on integration of the converter only. Since dc-dc converters can be used both in the charging and the propulsion mode, their integration was a logical aspect to consider. Moreover, the majority of inverters are also capable of performing rectification process. Therefore, their potential within the charging process could be easily

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identified. This section discusses integrated chargers that integrate only a converter into the charging process. Therefore, the propulsion machine in these topologies is not used for charging purposes.

A. Dc-dc Converter Performing Function of a Dc-dc Converter (Fig. 1)

Probably the most obvious part of EV powertrain that is suitable for integration into the charging process is the dc-dc converter. In the propulsion mode it converts usually low voltage of a battery into a suitable voltage for feeding an inverter. On the other hand, it can play an inverse role in the charging process by lowering the rectified voltage of the grid to reach the voltage level of the battery (Fig. 1). The only requirement for the integration is that the converter has to be bidirectional.

In [9] it is shown how a dc-dc Cuk converter, which is used for driving a dc machine of a pallet truck, can be integrated into the single-phase charging process. Since the converter is isolated, it also provides valuable isolation for the charging process. An obvious drawback is that it requires a separate, non-integrated element for grid voltage rectification.

B. Dc-dc Converter Performing Function of a Rectifier (Fig. 2)

In order to avoid a non-integrated rectifier, a rectifying role of a dc-dc converter is considered in [10-11] (Fig. 2). In propulsion mode switches S_1, S_2 and S_3 are used, making the topology an equivalent of a bidirectional buck-boost dc-dc converter. Operation of the switches S_2 - S_5 is required in the charging mode, and the active circuit during this mode of operation is highlighted in Fig. 2. Operation is based on a bridgeless rectification. Although the solution does not need a separate rectifier, it still requires a lot of non-integrated switches and diodes.

C. Dc-dc Converter Performing Functions of Both Rectifier and Dc-dc Converter (Fig. 3)

In order to take further advantage of a dc-dc converter, its integration into both charging stages (rectification and dc-dc conversion) is considered in [12]. The drivetrain has three bidirectional dc-dc converters (Fig. 3). In propulsion mode switches S_1 and S_2 are closed, thus converters are placed in parallel. The topology is particularly suitable for taking an advantage of interleaving switching strategy, in order to reduce battery current ripple. This means that carriers of the three converters are mutually shifted by one third of the switching period. For the charging process switches S_1 and S_2 have to be opened leaving two windings disconnected. Single-phase grid terminals are attached to the two newly formed ends of the two windings. Now, it is obvious that the group of two dc-dc converters connected as in Fig. 3, have the same topology as a full bridge bidirectional boost rectifier. Therefore, in this mode they are used for rectification of the grid voltage. From Fig. 3 it can be seen that the output of the rectification stage is connected to the remaining dc-dc converter. It can now be used for transforming the rectified voltage to a voltage that is appropriate for charging the battery. Hence, in the charging process a dc-dc converter is used both as a rectifier and as a dc-dc converter.

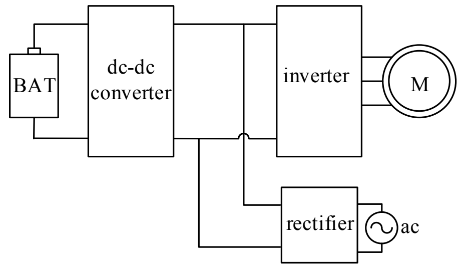


Fig. 1. Integrated dc-dc converter performing the dc-dc voltage conversion during the charging process.

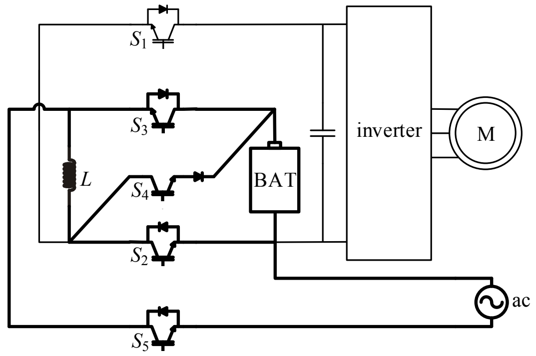


Fig. 2. Dc-dc converter utilized as a rectifier.

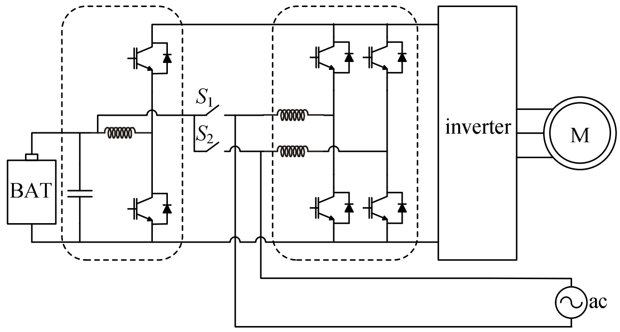


Fig. 3. Dc-dc converter utilized both as a rectifier and as a dc-dc converter.

D. Voltage Source Inverter (VSI) Performing Function of a Dc-dc Converter (Fig. 4)

Typical EV employs an inverter for driving the machine. In [13] it is shown how the inverter can be used as a dc-dc converter. The topology does not require reconfiguration between the propulsion and the charging mode, and it is presented in Fig. 4. In charging mode all switches are disabled except S_1. Switch S_1 together with diode D_1 and inductor L form a dc-dc converter. It can be seen that a separate rectifier and inductance are still required. A very similar integrated topology and the operating principle are discussed in [14] as one of the charging options.

E. VSI Operating as a Rectifier (Fig. 5)

In order to avoid the need for a separate rectifier, [15-20] consider utilization of VSI in the rectifying mode. The topology of [15] is shown in Fig. 5. For the charging mode switch S_1 has to be opened in order to prevent current flow in the machine. Single-phase grid voltage is applied to two inverter legs through inductor *L*, which is a non-integrated element. The two legs operate as a full bridge bidirectional boost rectifier. From Fig. 5 it can be seen that a separate rectifier is not required. However, the topology still requires a separate inductor and hardware reconfiguration between the operating modes.

F. CSI Operating as a Rectifier (Fig. 6)

The utilization of current source inverter (CSI) in EVs is proposed in [21], mainly in order to avoid the need for a costly and bulky high performance dc-bus capacitor. Instead, an inductor *L* is used as the energy storage (Fig. 6). Three ac filter capacitors are still required, although they are of much smaller capacitances. The use of voltage-to-current source circuit (V-I converter) is considered in order to add battery-charging capability to the topology, so that the same direction of current in the inductor *L* can both charge and discharge the battery. This feature is also useful for dynamic braking in propulsion mode. In addition to that, the V-I converter provides the drive with capability to control and maintain dc bus current in low speed region, when the machine's back EMF is substantially lower than the battery voltage. It includes two diodes and two switches. The use of diodes in CSI bridge (Fig. 6) can be avoided if reverse-blocking IGBTs (RBIGBTs) are utilized.

Charging process requires hardware reconfiguration in order to disconnect the machine from the CSI bridge. A single-phase voltage source can be directly applied between two CSI legs. An advantage of the topology is that there is no need for an inductor in between, which would otherwise have to be a non-integrated element. Another advantage is that it is capable to both buck and boost the output voltage. Thus, it can operate even when the battery voltage is much lower than the grid voltage.

G.MMC Operating as a Rectifier (Fig. 7)

The utilization of modular multilevel converters (MMCs) in vehicular applications has many benefits. In propulsion mode it can be used both for motor control and at the same time for energy balancing between the battery cells. Thus, it can operate as a battery management system as well. An additional benefit of the system is presented in [22-23]. It is shown that the charging mode can be easily accomplished by disconnecting the machine from the MMC and connecting grid voltage terminals to it (Fig. 7). In [22] it is shown that an additional inductor at the grid side is not required since voltage THD is below the value acceptable by standards due to high number of modules. From Fig. 7 it can be seen that only two MMC phases are connected to the grid. Nevertheless, zero-sequence current can charge the remaining phase through dc-bus voltage. For this, the dc

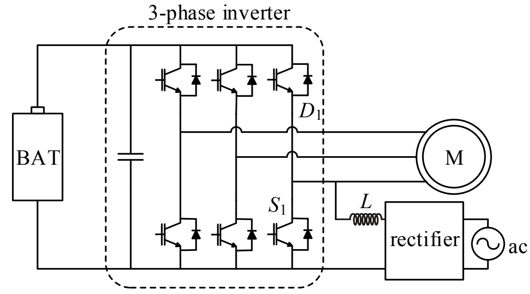


Fig. 4. VSI utilized as a dc-dc converter.

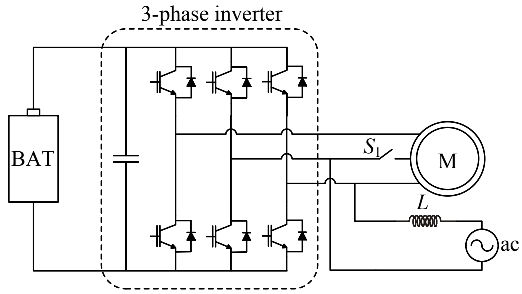


Fig. 5. VSI utilized as a rectifier.

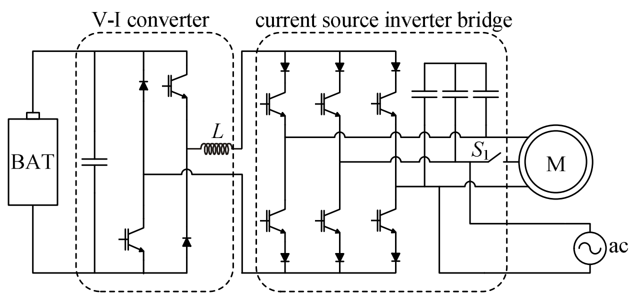


Fig. 6. CSI utilized as a rectifier.

-bus voltage should be governed by the two grid-connected phases.

III. TOPOLOGIES INCORPORATING CONVERTER AND SR MACHINE INTO THE CHARGING PROCESS

As can be seen from the previous Section, most of the topologies that integrate only a converter in the charging process require a separate inductance on the grid side. Moreover, some of them require switches to mechanically detach the machine from the rest of the circuit. In order to try to overcome some of these problems the integration of a propulsion machine, to perform the role of a filter inductance, was proposed. Although until recently PM machines were a preferable type of propulsion machines in EVs, the limited reserves of rear-earth materials may slow down their further use. On the other hand, SR machines are rear-earth-free and have many advantages that are valuable in EV sector, like low cost, high robustness and reliability, and capability to operate at high speeds. This section discusses topologies that allow integration of SR machine into the charging process.

A. Converter and SR Machine Performing Function of a Dc-dc Converter (Fig. 8)

Topologies that utilize SR machine and converter in the function of a dc-dc converter are presented in [24-26]. The topology of [24] is shown in Fig. 8. Switches S_6 and S_7 exist in order to allow the topology to operate as a part of a plug-in hybrid electric vehicle (PHEV), otherwise they could have been replaced with a short circuit. During the charging process switch S_5 is always opened. The topology can both buck and boost the output voltage. The boost mode is applied when the voltage of the battery is higher than the one of the grid. In this mode switch S_4 is always turned on, while switches S_1-S_3 are operated simultaneously in order to make the topology an equivalent of a boost converter. On the other hand, when the battery voltage is lower than the grid voltage, switches S_1-S_3 are always turned off and switch S_4 is utilized in order to convert the topology into an equivalent of a buck converter. SR machine windings are utilized as inductances in both buck and boost operating modes.

While [25] considers a similar topology and operating principles, [26] proposes a different topology which is again capable of both buck and boost operation. However, in addition to a diode bridge it demands further non-integrated components like a switch and three diodes.

B. Converter and SR Machine Operating as a Dc-dc converter and a Transformer (Fig. 9)

Although galvanic isolation during the charging process is not mandatory, it can greatly facilitate compliance with grid standards and regulations. In [27-32] it is shown how SR machine can be used as a transformer in order to provide isolation for the charging process. For this purpose, the SR machine has to have at least two closely coupled windings that are used as transformer primary and secondary winding. The converter part that is connected to the machine winding on the battery side can be utilized as a dc-dc converter.

The topology utilized in [27] is shown in Fig. 9. The left part of the Fig. 9 shows a C-dump converter which is utilized for the propulsion purposes. It also serves as a dc-dc converter during the charging mode. The right part of Fig. 9 is required solely for a connection to a high voltage of the grid, and is used only during the charging process. The SR machine has two phase windings that are used for propulsion (L_1 and L_2) and an additional winding L_3, which is closely coupled with one of the phase windings (L_2). The additional winding L_3 is used only during the charging mode in order to provide galvanic isolation from the grid. Together with the switch S_3 and battery-side circuit components (winding L_2, diode D_1 and capacitor C_1), it forms a fly-back converter. Hence, the topology can perform charging of a battery that has either higher or lower voltage than the grid. The fly-back converter (which is a buck-boost converter that contains a transformer instead of the inductor) is highlighted in Fig. 9. When the energy is accumulated in the capacitor C_1, the inductor L_4, switch S_4 and diode D_2 are used to transfer it into the battery. Although the topology provides isolation, its downside is that it still demands non-integrated components, such as a rectifier and other components that are shown on the right-hand side of Fig. 9.

C. Converter and SR Machine Performing Functions of both Rectifier and Dc-dc converter (Fig. 10)

Although in all topologies discussed in the previous two subsections a SR machine is integrated into the charging process, its converter operates only as a dc-dc converter.

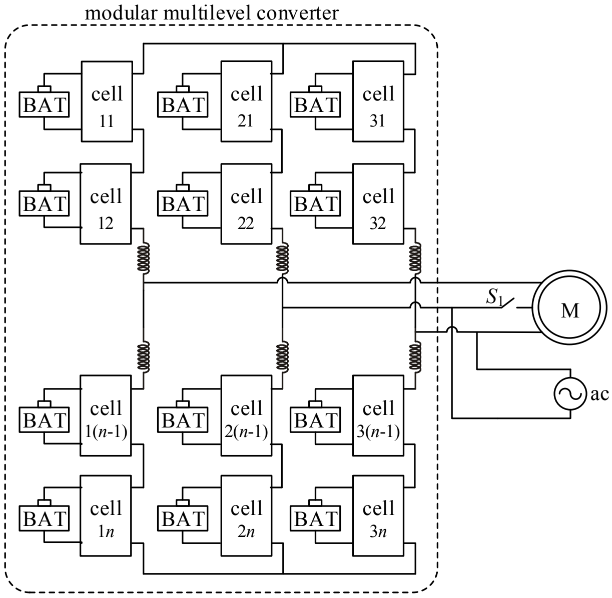


Fig. 7. MMC utilized as a rectifier.

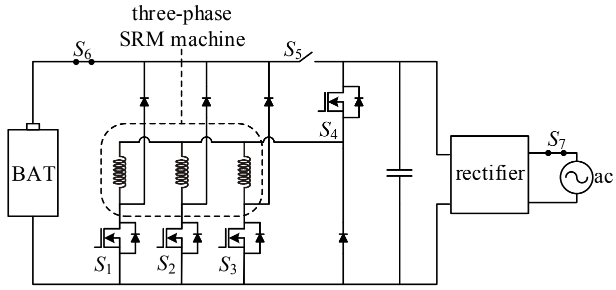


Fig. 8. SRM drivetrain utilized as a dc-dc converter.

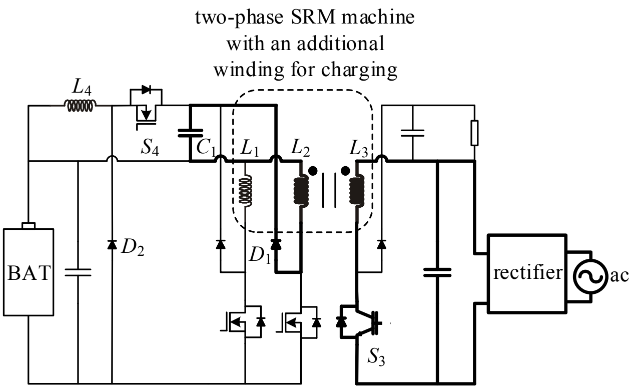
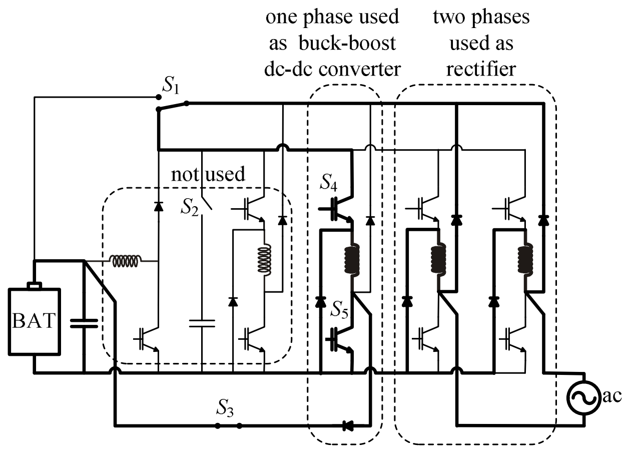


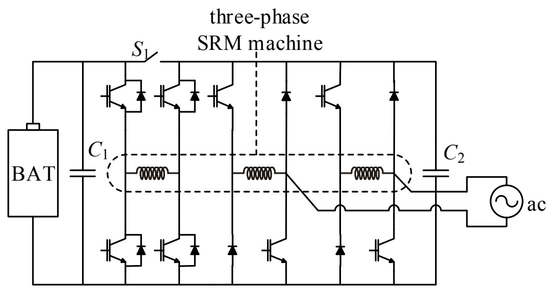
Fig. 9. SRM drivetrain utilized as a dc-dc converter and a transformer.

Thus, it cannot rectify the alternating voltage of the grid, and, therefore, a separate, non-integrated rectifier is required for this purpose.

In order to attempt to further reduce the cost of the system, the operation of a SR machine and its converter functioning as both the rectifier and dc-dc converter is proposed in [33-35]. The topology of [33] is shown in Fig. 10a. A dc-dc boost converter, whose purpose is to provide a well regulated dc-link voltage for the propulsion mode is not used during the charging process. The utilized components during the charging mode are highlighted in Fig. 10a. At first, two converter phases are utilized as a rectifier, with machine windings being employed as input filters. Then, when the grid voltage is rectified, the third phase acts as a dc-dc buck-boost converter in order to adjust the voltage to a value required by the battery. The fourth



a)



b)

Fig. 10. SRM drivetrain utilized as both rectifier and a dc-dc converter. Topology with: a) four phase, b) three-phase SRM.

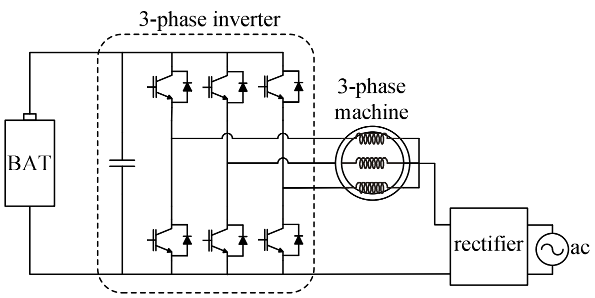


Fig. 11. VSI and machine utilized as a dc-dc converter.

phase is not used during the charging process. In order to reduce switching losses, switch S_4 is set to be permanently on, while S_5 is controlled by PWM.

Another integrated solution, based on a four-phase modified Miller converter is presented in [34]. The topology is made using off-the-shelf three-phase intelligent power modules, and in the charging mode it operates as buck-boost or buck PFC charger. Like the previous topology, it does not need externally added rectifier in order to perform charging.

Finally, the charging topology that is proposed in [35] is shown in Fig. 10b. The two capacitors C_1 and C_2, which are paralleled in the propulsion mode are separated by switch S_1 during the charging process, in order to allow two-stage operation. Similarly as in the previous two topologies, the grid voltage gets rectified by two converter phases that are attached to it. However, the difference is in the third phase (the one that is not connected to the grid). As can be seen, some power electronic components are added to its components in order to make a full bridge bidirectional converter. Now currents of both directions can flow through that phase. Therefore, it can be used as bidirectional dc-dc buck-boost converter, allowing V2G operation.

IV. Topologies Incorporating Converter and IM or PM Machine into the Charging Process

As already noted, IM and PM machines are preferred machine types for commercial EVs, and can be found in most of them. This Section discusses manners of their integration into a single-phase charging process.

A. VSI and Machine Performing Function of a Dc-dc Converter (Fig. 11)

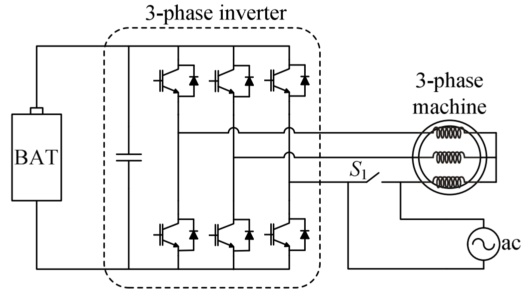
Proposals for utilization of the inverter and a machine for the function of a dc-dc converter are presented in [14] and [36-40]. The common scheme of [36-40] is shown in Fig. 11. It can be seen that the grid voltage is rectified by a separate non-integrated rectifier. Terminals of the rectified voltage are connected between the negative dc-bus and machine's neutral point. Since the neutral point is accessible, there is no need to either disconnect machine windings from each other, or to perform any other sort of hardware reconfiguration. If the three inverter phases are operated simultaneously (with the same modulation signals), they form a bidirectional dc-dc boost converter together with the machine. If the rectifying part is bidirectional as well, like in [40], the topology is capable of V2G operation. However, this is at the expense of additional switches in the rectifier. Since three legs are operating in parallel, the interleaving process can be employed in order to reduce grid current ripple, as shown in [37-38].

An additional aspect of [14] (on top of the one already covered in Section II-D) is that it proposes a topology similar to the one shown in Fig. 11. The difference is that one terminal of the rectified voltage is connected to a machine's phase, rather than to its neutral point. Switches belonging to that leg are not operated, while the remaining two phases are utilized in order to form a bidirectional dc-dc converter, similar to [36-40]. As in [37-38] the inter-leaving process can be applied, although now only in conjunction with two legs.

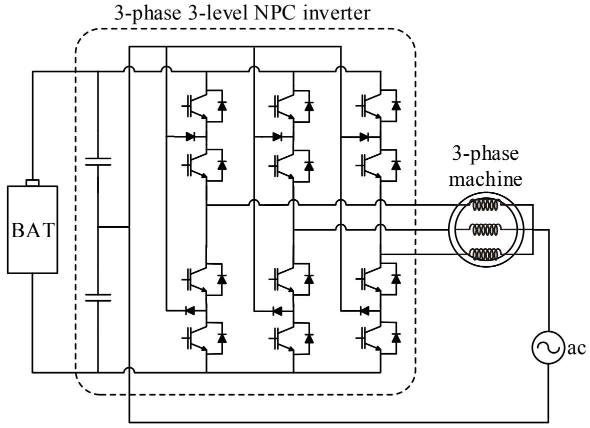
If topologies covered in this subsection are compared with those of Section II-D (Fig. 4), it can be seen that they keep their advantages but do not require a separate inductor in order to achieve the charging process. Instead, machine windings are utilized for this purpose. Moreover, charging power is spread across more than one leg, allowing higher power operation. However, both groups of topologies require a separate rectifier.

B. VSI and Machine Performing Function of a Rectifier (Fig. 12)

An integrated EV drivetrain that does not require a separate rectifier for the charging purposes is patented in [41], Fig. 12a. It requires a hardware reconfiguration in order to detach a machine's phase from the inverter and connect single-phase grid terminals between the two. The obtained scheme and operating principles are similar as in Section II-E (Fig. 5). However, a separate inductor is not required since machine windings are used for this purpose. The topology operates as a full bridge bidirectional boost rectifier during the charging mode, and the only requirement is that the battery voltage has to be higher than the peak of the grid voltage. V2G operation is achievable thanks to the bidirectional nature of the inverter.



a)



b)

Fig. 12. VSI and machine utilized as a rectifier. Topologies with the equivalent scheme of: a) full bridge, b) half bridge boost rectifier.

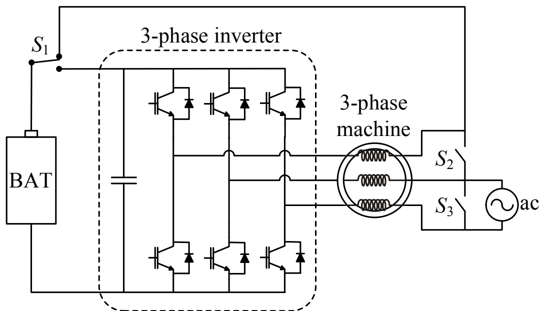


Fig. 13. VSI and machine utilized as both a rectifier and a dc-dc converter.

Another, and to some extent similar, integrated charger is presented in [42]. It employs inverter components as a resonant rectifier, and provides isolation from the grid. However, it utilizes more complex circuitry based on thyristors.

A topology that does not need hardware reconfiguration between the operating modes is presented in [43], Fig. 12b. It utilizes machine's neutral point and dc-bus mid-point as connection terminals for a single-phase grid. Diodes of the employed three-level NPC (neutral point clamped) converter that are connected to the dc-bus mid-point are not utilized during the charging process. In that mode, the inverter operates as having two levels only. The principle of operation is similar as for the topology of Fig. 12a. The difference is that the converter is operated as half bridge rather than full bridge boost rectifier. Since three inverter legs are connected to the same grid terminal, the utilization of interleaving process is proposed in order to reduce grid current ripple.

C. VSI and Machine Performing Functions of both Rectifier and Dc-dc Converter (Fig. 13)

Usage of an inverter and a machine for doing the tasks of both rectifier and dc-dc converter is proposed in [44-47], in order to avoid limitation that battery voltage has to be higher than the peak value of the grid voltage. The scheme of [46-47] is given in Fig. 13. For the charging mode from a single-phase grid, switches S_1 and S_2 have to be opened, and the switch S_1 has to be in the upper position, in order to connect the battery to one of the phases with an open end. The other two open-end windings are connected to a single-phase grid. Together with the associated inverter legs these two windings form a full bridge bidirectional boost rectifier, which is the first stage of the converter. The remaining machine winding and its associated inverter leg stand between the rectified grid voltage and the battery. Therefore, they can be utilized as a dc-dc buck converter. Since both dc-dc converter and full bridge boost rectifier are bidirectional, the opposite direction of power flow is viable, allowing V2G operation.

If the converter configuration during single-phase charging mode of operation is compared with the one from Section II-C (Fig. 3), it can be seen that they employ exactly the same charging topology. They both require hardware reconfiguration, and use elements that are already on-board EV to serve as input inductors. However, machine's windings rather than pure inductors are now used to perform the function of a filter. The advantage is that in this case a drivetrain does not have to possess a dc-dc converter in order to have its functionality during the charging operation.

D. Topologies Using a Machine with OeW (Fig. 14)

Integration of a machine with open-end winding (OeW) topology into the charging process is proposed in [48-49]. In [48] a machine supplied from two isolated power sources (two batteries) is considered. Instead of having two separate chargers, the utilization of a single charger is proposed (Fig. 14a). The non-integrated charger is capable of charging only the battery to which it is connected. However, the second battery can be also charged from the first, by utilizing windings of the machine and the two on-board inverters. The charging of the secondary battery can be performed both while the vehicle is parked and when it is running.

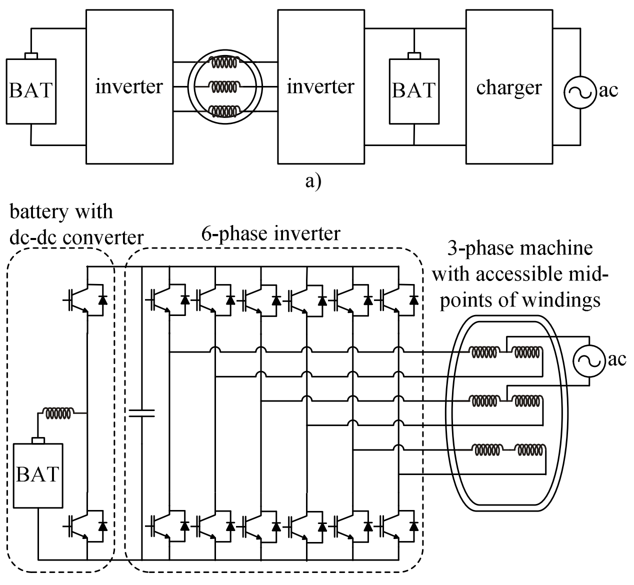


Fig. 14. Integrated topologies with a machine in OeW configuration: a) with two isolated batteries, b) with a single battery.

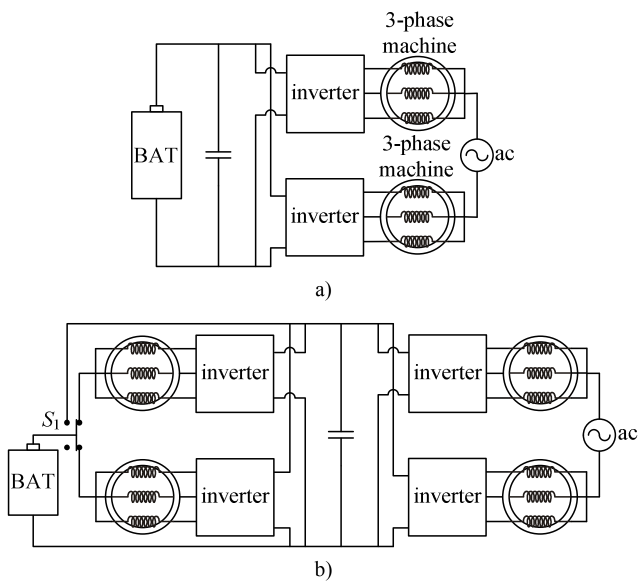


Fig. 15. Topologies based on: a) two-motor drive, b) four-motor drive.

An OeW topology supplied from a single voltage source is proposed for integration into the charging process in [49]. The topology is presented in Fig. 14b. It employs a three-phase machine that has accessible mid points of its windings (an equivalent of a symmetrical six-phase machine). During the charging mode a single-phase grid voltage is applied between two windings' mid points. The remaining winding which is not connected to the grid and its associated inverter legs are not utilized. Active inverter legs that are connected to the same phase of the machine are controlled with the same modulation signals. By doing so it is accomplished that the same currents flow through two halves of each winding, but in the opposite direction. Thus they cancel each other's field, and there is no field appearing in the rotor of the machine. Therefore, four active inverter legs operate as two pairs of legs, and their equivalent circuit during the charging mode is a full bridge bidirectional boost rectifier. When the grid voltage is rectified, an on-board dc-dc converter is utilized to adjust the voltage level. Since the vehicle is equipped with bidirectional dc-dc converter, and full bridge boost rectifier is capable of bi-directional operation, V2G mode is viable.

Based on the same operating principle a topology employing a single inverter is presented in [50]. However, unlike in [49] it requires hardware reconfiguration between the propulsion and the charging mode of operation.

E. Topologies Using Multiple Machines (Fig. 15)

Integration of multi-motor drives into the charging process is considered in [51-59]. A two-motor drive integrated charging topology shown in Fig. 15a is considered in [51-52]. A single-phase grid is connected directly between two isolated neutral points of the two machines. Therefore, hardware reconfiguration is not necessary. By controlling inverter legs belonging to the same motor using the same modulation signal, the circuit becomes an equivalent of a single-phase full bridge bidirectional boost rectifier. Therefore it has the same equivalent circuit like topologies from Fig. 5, Fig. 12a and Fig. 14b. Naturally, V2G operation is viable.

The application and beneficial influence of the interleaving process on the above discussed topology is considered in [53-54]. A somewhat similar galvanically isolated integrated charger, based on a machine with dual windings rather than on multiple machines, is presented in [55]. Finally, an attempt of further topological improvement of the integrated charger from [51-52] is made in [56].

A two-motor drive that in the charging mode performs functions of both rectifier and dc-dc converter is proposed in [57]. Windings of the first motor and diodes of the associated inverter are used for rectification of a single-phase voltage. The second stage consists of the second motor and its inverter, which together perform the function of a dc-dc buck-boost converter.

Finally, an integrated charger based on four-motor drive is proposed in [58-59]. For charging mode to take place it is necessary to disconnect the positive terminal of the battery from the dc-bus and to connect it to two isolated neutral points of two machines (Fig. 15b). A single-phase grid voltage is applied to the isolated neutral points of the remaining two motors. The two grid-connected motors, together with their inverters, form a single-phase full bridge bidirectional boost rectifier. Similarity of this stage with the topology of Fig. 15a can be easily noticed. However, the difference is in the second stage, which consists of two battery-connected motors and their inverters. Here it is employed in order to form two bidirectional paralleled dc-dc buck converters, which can control battery charging current or battery charging voltage.

F. Topologies Using Multiphase Machines (Fig. 16)

Integrated multiphase drive topologies are presented in [51] and [60-62]. In [51] the use of a six-phase machine (Fig. 16a) instead of two three-phase machines is proposed as an additional aspect of the patent. The topology is based on the same operating principles as the one in Fig. 15a. It again requires six inverter legs, and the only difference is that a single machine with six windings is utilized instead of two three-phase machines. A very similar topology is considered in [60] based on a six-phase interior permanent magnet synchronous motor (IPMSM).

A somewhat different configuration, utilizing a machine with two sets of delta connected three-phase windings, is proposed in [61]. The grid terminals are connected to two inverter legs rather than to machine isolated neutral points as in [51, 60].

Finally, a nine-phase drive was proposed for integration into the charging process in [62]. As can be seen from Fig. 16b, the machine has three sets of three-phase windings. During the charging process a single-phase grid is applied between two isolated neutral points of the machine. The third set of windings and corresponding inverter legs are not employed during the charging process. The two active sets are utilized in the same manner as in [51] in order to make a single-phase full bridge bidirectional boost rectifier. Inclusion of an optional dc-dc converter is considered in order to allow charging of batteries with lower voltages.

It should be noted that none of the topologies covered in this subsection requires hardware reconfiguration between the charging and propulsion mode. Moreover, none requires non-integrated inductances, switches or diodes in order to perform rectification. They are all capable of V2G operation.

An example of experimental results that can be obtained with the topology of Fig. 16a is shown in Fig. 17. The experiment is performed with an asymmetrical six-phase induction machine. The capability of the topology to return the battery energy back into the grid was considered. The experiment is performed with single-phase voltage of 240V rms. The dc-bus voltage is set to 600V. The interleaving process is employed in order to reduce grid current ripple. From Fig. 17 it can be seen that the grid current is in phase opposition with the grid voltage, demonstrating that the power is injected into the grid. The unity power factor is obvious. It can be seen that machine’s current is in phase with the grid current, only three times lower. The reason is that each grid terminal is connected to three phases of the machine. From Fig. 17 it can be seen that grid current has low switching ripple, which is a consequence of the employment of the interleaving process.

V. COMPARISON OF TOPOLOGIES

In this Section the surveyed topologies are quantitatively compared. For that purpose each group is represented with a single topology. The comparison is based on additional requirements that integrated chargers may have. Three aspects are considered. The first one is the need for additional switching devices or diodes. As additional components, they increase the cost of the charger. The second aspect is the need for a separate inductor, which presents additional cost, as well as weight. Finally, the need for hardware reconfiguration is taken into consideration. The comparison is given in Table I.

It can be seen that some of the topologies can perform charging without any additional switches, diodes or inductors, and at the same time do not require hardware reconfiguration. However, the qualitative gradation of topologies is much more complex. In order to perform one, all pros and cons of each solution should be carefully evaluated.

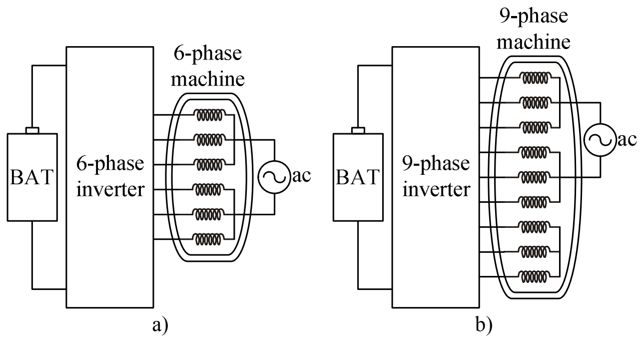


Fig. 16. Integrated chargers based on: a) six-phase, b) nine-phase machine. The converter and the machine are used as a rectifier and filtering inductances.

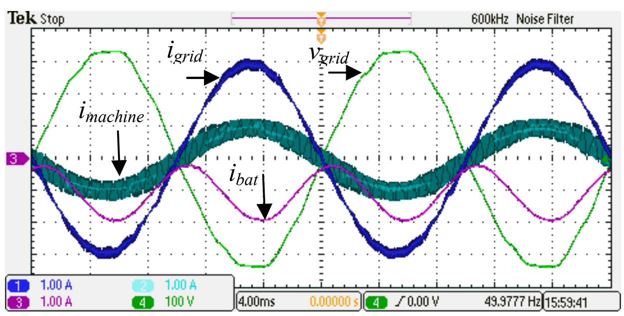


Fig. 17. An experimental example of V2G operation of the integrated topology shown in Fig. 16a.

TABLE I
QUANTITATIVE COMPARISON OF TOPOLOGIES.

Topology	Does not require additional switches or diodes	Does not require additional inductive element(s)	Does not require hardware reconfiguration
Fig. 1	×	✓	✓
Fig. 2	×	✓	✓
Fig. 3	✓	✓	×
Fig. 4	×	×	✓
Fig. 5	✓	×	×
Fig. 6	✓	✓	×
Fig. 7	✓	✓	×
Fig. 8	×	✓	×
Fig. 9	×	×	✓
Fig. 10a	✓	✓	×
Fig. 10b	×	✓	×
Fig. 11	×	✓	✓
Fig. 12a	✓	✓	×
Fig. 12b	✓	✓	✓
Fig. 13	✓	✓	×
Fig. 14a	×	×	✓
Fig. 14b	✓	✓	✓
Fig. 15a	✓	✓	✓
Fig. 15b	✓	✓	×
Fig. 16a	✓	✓	✓
Fig. 16b	✓	✓	✓

VI. CONCLUSION

Integrated on-board single-phase battery chargers for EVs are reviewed in this paper. Their operating principles during the charging process are elaborated. The analysis commences with configurations that integrate only the converter into the charging process, leaving the machine in idle mode during the charging process. It is followed by topologies giving both converter and SR machine the double functionality. The final analysed group consists of topologies incorporating a converter and IM or PM machine into the charging process. Finally, topologies from all three groups are quantitatively compared based on the use of additional elements and the requirement of hardware reconfiguration between the operating modes.

It should be noted that an important aspect of the integrated chargers is charging efficiency. However, a multitude of topologies is introduced only at conceptual level (by patents), showing no details about their performances. Moreover, majority of the topologies that are validated employ laboratory based prototypes, and therefore are not optimized for vehicular applications. This to a large extent hinders the efficiency analysis, which would probably require investigation of all topologies by simulation means.

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