IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Traction inverter with integrated charger: practical realisation and experimental study

To cite this article: K M Sidorov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **643** 012031

IOP Conf. Series: Materials Science and Engineering **643** (2019) 012031 doi:10.1088/1757-899X/643/1/012031

Traction inverter with integrated charger: practical realisation and experimental study

K M Sidorov*, A G Grishchenko, B N Sidorov

Moscow Automobile and Road Construction State Technical University (MADI), Leningradsky prospect, 64, Moscow, 125319, Russia

* E-mail: kmsidorov@gmail.com

Abstract. This article presents some practical designs for combining control functions of AC traction motor and high voltage on-board vehicle battery pack charge using single hardware components and common power circuit. Basic charger and traction inverter integration circuit designs as well as conditions necessary for keeping their power equivalent are described in the article. Based on these circuit designs, the new traction inverter with integrated charger design is suggested. This design has the advantage of high-power density, optimal weight and size ratio and relatively simple control system realisation. The suggested design is recreated in a voltage converter experimental sample. The study results of the created design basic functional characteristics are provided in the article. Traction inverter with integrated charger practical realisation results can be used in the advanced vehicle (electric vehicles, hybrid electric vehicles) development and construction as well as in autonomous power supply systems.

1. Introduction

An electric vehicle (EV) powertrain system, as a rule, includes a set of individual voltage converters including an electric motor traction inverter and an on-board battery pack charger [1]. These components are functional and autonomous. Unlike traction inverter, on-board battery charger [2] is useless during driving and rest of a vehicle. Thus, it is a unit which basically presents an unnecessary load for a vehicle. Moreover, power of such chargers is insufficient for a quick traction battery pack charging [3] which leads to EV performance reduction. As a result, the long distances EV exploitation becomes troublesome. On one hand, aforementioned circumstances are the rationale for the topicality of the electric vehicle powertrain system weight and size ratio improvement as well as the improvement of the power effectiveness and overall performance of EV. On the other hand, they are the reason of the increased demand for the charging infrastructure, given its challenged availability and development.

In order to resolve the stated issues, it is necessary to optimize the traction electric equipment system and implement some multifunctional circuit designs [4-10]. This article provides the practical realisation of such circuit design in relation to a traction inverter with integrated charger (TI with IC).

2. The existing electric motor and traction battery charge control function integration designs

At the present stage of technical equipment development, we have a vehicle traction electric circuit containing an on-board power source, solid-state converter and three-phase synchronous motor with separate excitation. In addition, the said motor stator windings have an option of external power source connection in order to provide the charge of an on-board power source through the solid-state

IOP Conf. Series: Materials Science and Engineering **643** (2019) 012031 doi:10.1088/1757-899X/643/1/012031

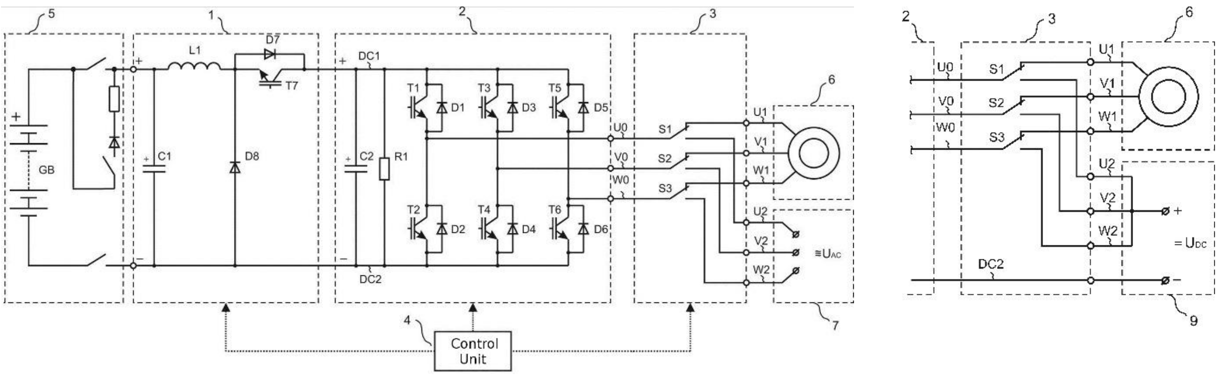
converter [11]. The given design is disadvantageously limited by the usage of electromagnetic synchronous motors with separate excitation only. This type of electric motors is not used in contemporary advanced electric motors, unlike more widely spread permanent magnet synchronous electric motors and traction squirrel-cage induction motors. Furthermore, the design realisation is hampered by the necessity to use a special configuration electric motor providing the output of all phase windings ends for external connections.

There are more hybrid electric vehicles (HEV) applicable devices which require several electric motors. According to the designs provided in the article, the charge circuit of a rechargeable energy storage can be created only if there are two special configuration electric motors and two traction inverters in the electric vehicle system [12, 13]. At the same time the windings of each electric motor have to be but wye connected with neutral terminal for further external AC voltage source connection. These are designs which require complex software and hardware algorithm implementation for traction power source charge energy conversion. The complexity is caused by the substantial semiconductor element quantity necessary for the energy conversion. This accounts for additional energy loss when charging the power source.

It is worth mentioning that there is one more flaw of the stated circuit designs which excludes the possibility of full-fledged usage of the most efficient and powerful three-phase networks as the external charger without additional voltage conversion. The quick charging of EV batteries by aforementioned designs can be achieved primarily by DC network or single-phase network usage. The use of a three-phase network instead of the analogous single-phase network for charge will provide the decrease the external power source current load approximately three-fold. These is a promising direction considering the increasing power consumption and the number of operating EV.

3. The TI with IC circuit design and operating principle

The TI with IC circuit design for further practical realisation is shown below in Figure 1a.



(a) (b)

Figure 1. Topology of the traction inverter with integrated charger power circuit for use with external (a) three-phase AC and (b) DC voltage source.

A TI with IC consists of a charging voltage converter (1), an inverter (2); a switching device (3), control unit (4). The charging voltage converter is connected to the traction battery pack (5) and contains the inductor (L1), the capacitor (C1), the semiconductor switch (T7), the semiconductor diodes (D7 and D8). The charging voltage converter output circuit is connected to the inverter busbars (DC1 and DC2). The inverter includes a number of transistor switches (T1-T6), in particular IGBT with the inverse diodes (D1-D6). The inverter phase outputs are connected to the switching device (3). The switching device consists of three power contacts (S1, S2, S3). Depending upon the TI with IC operation mode, power contacts provide the electric motor windings or three-phase AC voltage source (7) phases connection to the inverter phase outputs. The control unit (4) creates and transmits charging voltage converter, inverter, switching device control commands through the transmission channel (8).

The TI with IC can also contain the inverter negative DC busbar output which provides quick traction energy storage charging from DC voltage source (9). In this case the switching device phase outputs (U2, V2, W2) are united in one common point and connected to the DC voltage source positive pole. Additionally, the inverter negative DC busbar output is connected to the DC voltage source negative pole. The power circuit of the described design is shown in Figure 1b.

The TC with IC functions in a following way. The traction battery pack is connected to the charging voltage converter input circuit during driving. The diode (D7) provides traction source unhampered discharge current flow in the inverter circuit with no effect on the operation of the latter. The control unit creates commands for the commutation of the inverter semiconductor elements (T1…T6) according to a certain algorithm, particularly the sinusoidal algorithm or space vector pulse-width modulation. As a result of the mentioned semiconductor elements commutation the traction battery pack DC voltage converts into the regulated in terms of magnitude and frequency AC voltage in order to power and operate the electric motor both in motor operation and electric braking mode. Additionally, the powering of electric motor winding phases is carried out through normally closed power switching contacts of the switching device.

Power generated by a traction electric motor provides traction energy storage charge in the vehicle braking mode. At the same time a charging voltage converter can operate in two modes: a fully opened transistor switch (T7) mode or an energy storage charge pulse-width control mode.

An external three-phase AC source is connected to the switching device phase outputs (U2, V2, W2) in order to charge traction battery during the vehicle standby mode. This can be done by using special power circuits and cables designed for EVs. A traction battery in a charging mode is connected to a charging voltage converter input circuit. The control unit transmits the command to switch power contacts (S1, S2, S3) of the switching device through the transmission channel. Consequently, external three-phase voltage source is connected to the inverter phase outputs (U0, V0, W0). The rectification of the external three-phase AC voltage is carried out by the inverter semiconductor diodes (D1…D6). The inverter capacitor (C2) provides smoothing out the rectified voltage pulsation. The control unit creates and transmits control impulses for semiconductor switch (T7) commutation through the transmission channel according to the pulse-width control algorithm. This results in the conversion of the external source rectified voltage into the DC voltage for set magnitude traction energy storage charge as well as the charge current regulation. The capacitor (C1) and the charging voltage converter inductor (L1) provide DC voltage filtration in the traction energy storage charge mode. The semiconductor diode (D8) provides a necessary current flow for inductor (L1) discharge to the traction power source. The TI with IC circuit design and operation principle do not exclude the charge mode regulation of the traction energy storage by the inverter semiconductor switch (T1…T6) commutation.

There is another TI with IC circuit design option which is analogous to the design described above. The difference is that when charging from the external DC voltage source (9) (see Figure 1 b), the inverter semiconductor diodes (D1, D3, D5) are the charge current conductors given that the inverter DC negative busbar (DC2) is connected to the source negative pole.

The provided circuit design has following advantages: 1. It is possible to use in AC electric motors of various type and configuration; 2. There is no need to have the traction equipment of two electric motors and inverters for ensuring traction energy storage charge; 3. The software and hardware algorithm implementation for energy conversion is relatively simple; 4. It allows the use of three-phase networks with no additional voltage conversion; 5. It increases the power and speed of vehicle traction energy storage charging while decreasing the load on the external voltage sources; 6. It provides the improved weight and size ratio and better efficiency of the powertrain system.

4. The TI with IC design suggestions

The most important conditions for constructing an efficient and reliable voltage converter are: optimal capacitor operation temperature conditions, a minimized active resistance as well as inductance of capacitor bank dissipation and DC busbar inductance. The listed criteria are considered in the suggested TI with IC design.

The TI with IC design is a metal case (16) with two sections (see Figure 2). In the power electronic section (18) there are: transistor-diode power modules (1) on a liquid cooling device (5), gate drivers (4) set at the module gate terminals, snubber capacitors (3), laminated DC busbars (6), phase busbar (7), conductive pads (8), current sensors (9), bus insulators (10). Power filter capacitors (2) are located at the cooling capacitor section (19). The capacitors are situated in a row, so that their power outputs (23) are in single line and in communication with the power electronic section through seal elements (14) (see Figure 3). The forced-air capacitor cooling is carried out by fans (12). The hot air is discharged out of the cooling capacitor section through the case ventilation holes (17). Positive and negative capacitor power outputs are electrically connected with the positive and negative DC busbars respectively. The busbars represent two separate conductive plates isolated by the insulators. Each of the conductive plates has a number of terminals (24), 90° bent towards the plate surface, which represent contact surfaces for the conductive pads and semiconductor gate terminals. A positive conductive plate (25) has a number of holes for negative capacitor power output non-contact pass-through. It also has holes for rotary electric connection with positive capacitor power outputs. A negative conductive plate (26) has a number of holes situated coaxially to the positive power capacitor outputs. The holes diameter is more than that of the power capacitor outputs in order to avoid the electric contact. The negative conductive plate also has a number of holes for rotary electric connection with negative capacitor power outputs. A control system (20) with its components and control circuits is situated under gate drivers in the screen part of the power electronic section. The length of the control circuits for semiconductor gate terminal commutation is minimal.

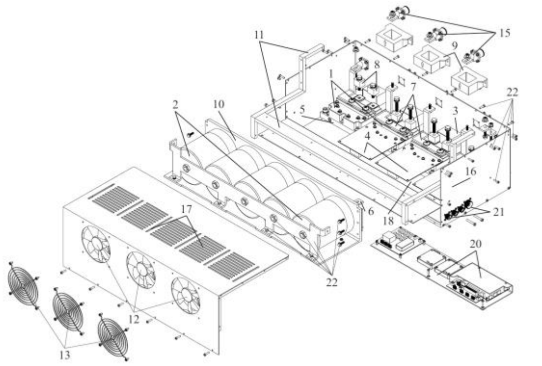


Figure 2. The TI with IC exploded diagram.

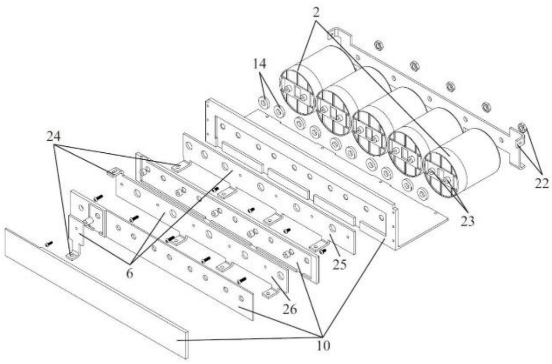


Figure 3. The filter capacitor bank with seal elements design and busbar configuration.

In the TI with IC operation process the thermal loss power in the semi-conductor modules is discharged through the liquid cooling device. The thermal stabilisation of power filter capacitor operation mode during the converter functioning is carried out by hot air convective drift through the ventilation holes. If the natural cooling is insufficient, the thermal stabilisation is done by the air flow created by fans.

The provided TI with IC design has following advantages comparing with suggestions demonstrated into [14, 15]: 1. It has an effective thermal discharge from filter capacitors using natural convection and forced-air cooling; 2. The power electronic section is effectively sealed though the length of the sealing joint is minimal; 3. The seal elements are unified for a wide type and size range of power capacitors; 4. The active resistance and laminated DC busbar dissipation inductance figures are low; 5. The transistor control circuit length is minimal; 6. The voltage converter design is compact and the space inside the metal case is efficiently used.

Technical solutions for traction inverter circuit and construction design provided in the article are implemented in a TI with IC experimental sample. The internal organisation of the TI with IC experimental sample is shown in Figure 4. In the course of the present study some experimental investigations of TI with IC basic operation modes have been conducted in order to evaluate the efficiency of the implemented technical solutions as well as functional advantages of the TI with IC experimental sample in practice.

5. The experimental investigations results

The main purpose of the study tests is practical (experimental) evaluation of TI with IC functional and parameter characteristics. The TI with IC sample test method consists of the experimental evaluation of the main characteristics by the direct and indirect measuring of the electric, traction power and mechanical parameters. The TI with IC testing was performed using an equipped test bench which included: load equipment, control devices, measuring and recording equipment. It is worth mentioning that during the bench testing a three-phase network was used as a power source with further AC into DC voltage rectification for powering the TI with IC. The TI with IC load was provided by a traction squirrel-cage induction motor and motor testing dynamometer.

The TI with IC operation evaluation results in characteristic traction electric drive operation modes, including acceleration, steady-state rotation and regenerative braking, are shown in Figures 5 and 6.

Figure 4. An actual TI with IC.

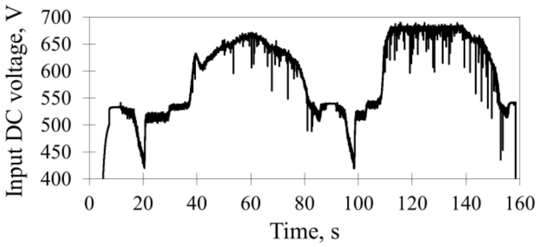


Figure 5. The change in input TI with IC voltage during the traction electric drive dynamic testing.

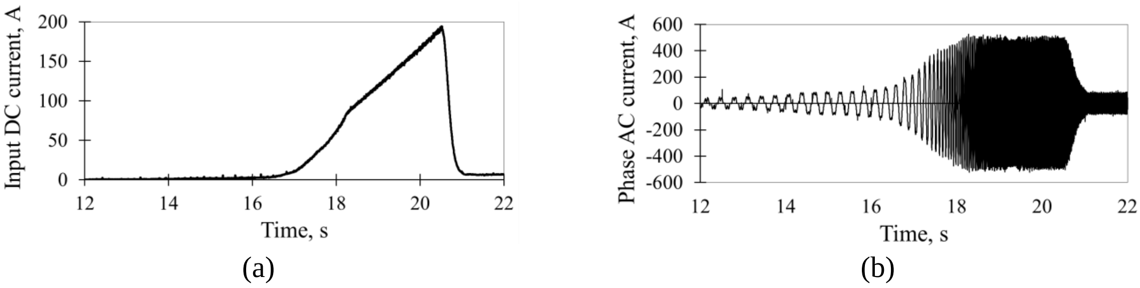


Figure 6. The change in a) input DC and b) output AC phase TI with IC currents during traction electric drive acceleration.

The following figures were documented during the TI with IC experimental study:
- peak output phase current - 355 A;
- peak input current in the acceleration mode - 195 A;
- rated input voltage - 540 V;
- peak voltage in the regenerative braking mode - 680 V;
- peak power in the acceleration mode (traction battery pack discharge) - 83 kW;
- peak power in the regenerative braking mode (traction battery pack charge) - 27 kW.

6. Conclusion

Development of advanced EVs and plug-in HEVs is closely connected to the charging infrastructure development. Still, conventional on-board battery charger usage causes substantial charge power limitation and, consequently, hampers the development. This obstacle can be overcome by stationary DC battery charger usage. However, the implementation of such charger stations is not a simple task and accelerated charge stations are not yet widely spread. Additionally, there are powerful three-phase networks available in places where supercharger stations are not expected anytime soon or are not expected at all. Thus, the extension of basic traction inverter functions is a topical issue. The unifying the EV and traction battery charge control tasks using the peak power and single hardware components can become an economically efficient solution of the discussed issues.

The technical TI with IC solutions shown in the present article provide the accelerated charge of an on-board vehicle battery pack at power levels equivalent to those of traction inverter, these solutions simultaneously improve the traction electrical equipment weight and size ratio, increase vehicle performance and reduce the load on the charging infrastructure. The practical realisation results of the TI with IC experimental sample design prove the possibility of unifying several functions in a single converter without any loss in its operational performance.

The solutions of the TI with IC experimental sample design are applicable not only in the transport sphere but can be successfully used in autonomous power supply systems, e.g. stabilising voltage converter based autonomous power plants, electric energy storages and renewable energy sources.

Acknowledgments
The article is part of the applied scientific research (RFMEFI57417X0170) conducted at Moscow Automobile and Road Construction State Technical University (MADI) and sponsored by the Ministry of Science and Higher Education of the Russian Federation.

References
[1] Stippich A et al 2017 Key components of modular propulsion systems for next generation electric vehicles 2017 *CPSS Trans. on Power Electron. and App.* **2** 249-58
[2] Yilmaz M and Krein P T 2013 Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles *IEEE Trans. on Power Electron.* **28** 2151-69
[3] Chen Z, Zhang Z, Zhao J, Wu B and Huang X 2018 An analysis of the charging characteristics of electric vehicles based on measured data and its application IEEE Access 6 24475-87
[4] Sakr N, Sadarnac D and Gascher A 2014 A review of on-board integrated chargers for electric vehicles 2014 16th European Conference on Power Electronics and Applications (Lappeenranta: IEEE) pp 1-10
[5] Pedrosa D, Gomes R, Monteiro V, Aparício Fernandes J C, Monteiro J, Afonso J L 2017 Model predictive control of an on-board fast battery charger for electric mobility applications CONTROLO 2016. *Lecture Notes in Electrical Engineering* **402** 679-89
[6] Su G and Tang L 2011 Current source inverter based traction drive for EV battery charging applications 2011 IEEE Vehicle Power and Propulsion Conference (Chicago: IEEE) pp 1-6
[7] Lacroix S, Laboure E and Hilairet M 2010 An integrated fast battery charger for electric vehicle 2010 IEEE Vehicle Power and Propulsion Conference (Lille: IEEE) pp 1-6
[8] Ma M, Chang Z, Hu Y, Li F, Gan C and Cao W 2018 An integrated switched reluctance motor drive topology with voltage-boosting and on-board charging capabilities for plug-in hybrid electric vehicles (PHEVs) *IEEE Access* **6** 1550-9
[9] Na T, Zhang Q, Tang J and Wang J 2018 Active power filter for single-phase Quasi-Z-source integrated on-board charger *CPSS Trans. on Power Electron. and App.* **3** 197-201
[10] Subotic I, Bodo N, Levi E, Dumnic B, Milicevic D and Katic V A 2016 Overview of fast on-board integrated battery chargers for electric vehicles based on multiphase machines and power electronics *IET Electr. Power Appl.* **10** 217-29
[11] Dupuy P 2010 World Intellectual Property Patent Publ. No. WO2010012924A2
[12] Ichikawa S 2008 JP Patent No. JP4144646B1
[13] Ishii K, Kamaga T, Karami M and Fukui M 2007 JP Patent No. JP4332861B2

IOP Conf. Series: Materials Science and Engineering **643** (2019) 012031 doi:10.1088/1757-899X/643/1/012031

[14] Hebert M 2015 DE Patent No. DE102014105114A1
[15] Talanin J V 2006 RU Patent No. RU2280294C2