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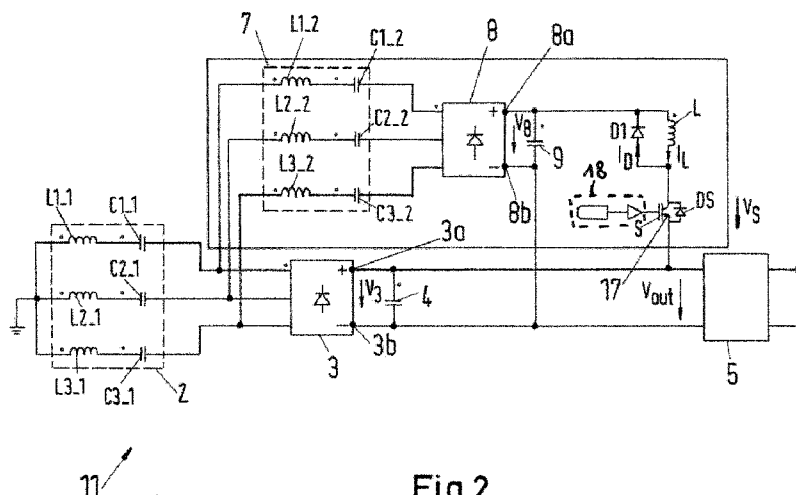


Fig.2

(57) **Abstract:** The invention relates to a circuit arrangement, in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle, wherein the circuit arrangement (11) comprises a first inductive element of a first receiving device (2) for receiving an alternating electromagnetic field and to generate a first induced electric output voltage, wherein the circuit arrangement (11) further comprises a first rectifier (3) for rectifying the first induced electric output voltage, wherein the circuit arrangement (11) comprises a first inductive element of at least one additional receiving device (7) for receiving the alternating electromagnetic field and to generate another induced electric output voltage, wherein the circuit arrangement (11) further comprises an additional rectifier (8) for rectifying the other induced electric output voltage, wherein the circuit arrangement (11) further comprises at least one switching element (S), wherein the at least one switching element (S) is arranged within the circuit arrangement (11) such that in a first switching state of the switching element (S) a resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_3) of the first rectifier (3) and that in another switching state of the switching element (S) the resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_8) of the additional rectifier (8). Furthermore, the invention relates to a method of operating the said circuit arrangement, to a method of manufacturing a circuit arrangement and to a vehicle.

Circuit arrangement and method of operating a circuit arrangement

The invention relates to a circuit arrangement of a vehicle, in particular a vehicle-sided circuit arrangement of a system for inductive power transfer to the vehicle. Furthermore, the invention relates to a method of operating the said circuit arrangement. Further, the invention relates to a method of manufacturing a circuit arrangement and to a vehicle.

Electric vehicles, in particular a track-bound vehicle, and/or a road automobile, can be operated by electric energy which is transferred by means of an inductive power transfer. Such a vehicle may comprise a circuit arrangement, which can be a traction system or a part of a traction system of the vehicle, comprising a receiving device adapted to receive an alternating electromagnetic field and to produce an alternating electric current by electromagnetic induction. Furthermore, such a vehicle can comprise a rectifier adapted to convert an alternating current (AC) to a direct current (DC). The DC can be used to charge a traction battery or to operate an electric machine. In the latter case, the DC can be converted into an AC by means of an inverter.

The inductive power transfer is performed using two sets of e.g. three-phase windings. A first set is installed on the ground (primary windings) and can be fed by a wayside power converter (WPC). The second set of windings is installed on the vehicle. For example, the second set of windings can be attached underneath the vehicle, in the case of trams under some of its wagons. The second set of windings or, generally, the secondary side is often referred to as pick-up-arrangement or receiving device. The first set of windings and the second set of windings form a high frequency transformer to transfer electric energy to the vehicle. This can be done in a static state (when there is no movement of the vehicle) and in a dynamic state (when the vehicle moves).

Due to presence of a large clearance between the primary windings and the secondary windings, the operational behavior of this transformer is different than the behavior of

conventional transformers which have a closed magnetic core with negligible or small air gaps. The large air gap results in smaller mutual inductive coupling and larger leakage inductances.

The leakage inductance usually acts as a series inductance with each winding of the primary windings and of the secondary windings. To be able to transfer high power levels, it is usually necessary to use an adequate capacitance in order to compensate the reactance of the inductors at an operating frequency of e.g. 20 kHz. The combination of the (leakage) inductance and the (compensating) capacitance forms a resonant circuit. A perfect impedance cancellation happens if impedance values of the inductance and the capacitance are chosen such that the natural resonance frequency of the resonant circuit is equal to the operating frequency. Such a resonant circuit is tuned.

In a tuned resonant circuit, an impedance of the resonant circuit is zero at the first harmonics of the operating frequency. Therefore, the induced voltages appear at the output terminals of the resonant circuit regardless of the current value. These voltages are then rectified by e.g. a three-phase rectifier with its output connected to a vehicle DC bus.

The rectifier can be a diode bridge which is a simple, durable and robust unit. On the other hand, it has no controllability and therefore, the DC bus voltage level is mainly determined by the voltages induced in the resonant circuit of the pick-up or receiving device. It is not practically possible to control the DC bus voltage level using the present arrangement.

At any moment of time, the induced voltages in the resonant circuit of the receiving device depend on two factors, the primary current and the mechanical clearance, i.e. the air gap, between the primary windings and the secondary windings of the receiving device. The primary current is not strictly regulated and varies due to the variations WPC input voltage which is a DC input voltage. The instantaneous mechanical clearance, i.e. the air gap, between the primary windings and the secondary windings varies due to different reasons such as weight of the passengers, rail and wheel wear (e.g. in trams) or reduced tire air pressure (in e.g. busses and cars), oscillations in the vehicle suspension, wayside curvature and other reasons.

Although the acceptable voltage variation range on the vehicle-sided DC bus is quite large (for example 550 to 950 V), the combined effect of variations in the primary current and in

the mechanical clearance can lead to a wide voltage variation far beyond the acceptable range. In the cases where a narrow mechanical clearance variation range is not an option (due to mechanical constraints) it is furthermore mandatory to find another mechanism to keep the DC bus voltage in the appropriate range.

The patent application GB 1216184.0 (not yet published) discloses a circuit arrangement, wherein the circuit arrangement comprises an impedance and at least one rectifier for rectifying an AC voltage. An AC part of the circuit arrangement comprises the impedance, wherein the rectifier connects the AC part to a DC part of the circuit arrangement. The circuit arrangement further comprises at least one current control means for controlling a current flow in the AC part.

It is an object of the present invention to provide a circuit arrangement of a vehicle, in particular a vehicle-sided circuit arrangement of a system for inductive power transfer to the vehicle, and a method of operating said circuit arrangement by which a width of a voltage variation in a DC part of a vehicle-sided receiving device or in a DC bus of the vehicle can be reduced.

It is a basic idea of the invention to provide an additional inductive element, in particular an additional winding structure, which is able to receive an electromagnetic field and to generate an alternating current (AC) output voltage which is rectified by an additional rectifier. A switching element can be controlled such that either the output voltage of the existing rectifier is provided at output terminals of the circuit arrangement or the output voltage of the additional rectifier is provided at the output terminals of the circuit arrangement. Thus, two different output voltages with different voltage levels can be provided. This allows compensating unwanted voltage variations which are e.g. caused by variations in the primary current and/or the mechanical clearance between the primary winding structure and the secondary winding structure.

The present invention can be applied to any land vehicle (including, but not preferably, any vehicle which is only temporarily on land, in particular track bound vehicles, such as rail vehicles (e.g. trams), but also to road automobiles, such as individual (private) passenger cars or public transport vehicles (e.g. busses, including trolley busses which are also track bound vehicles).

A circuit arrangement, in particular a circuit arrangement of a vehicle, in particular an electric vehicle, for inductive power transfer to the vehicle, is proposed. The circuit arrangement can be part of the traction system of the vehicle. The circuit arrangement comprises a first inductive element of a first receiving device for receiving an alternating electromagnetic field and to generate a first induced electric output voltage.

In particular, the first inductive element can be provided by or comprise a secondary-sided winding structure of a transformer, wherein the transformer is used to transfer energy from primary windings, which can be installed in a ground providing a driving surface for a vehicle, to the vehicle. The circuit arrangement or elements of the circuit arrangement can be part of a pick-up arrangement of the vehicle, which can e.g. be installed at a bottom side of the vehicle. The first induced electric output voltage is an AC voltage. The circuit arrangement further comprises a first rectifier for rectifying the first induced electric output voltage. The first rectifier is electrically connected to the first inductive element of the first receiving device, e.g. by a current path.

According to the invention, the circuit arrangement further comprises a first inductive element of at least one additional receiving device. The additional receiving device, as the first receiving device, is arranged and/or designed such that the aforementioned alternating electromagnetic field, which is generated by a current flow through the primary windings, can be received also by the at least one additional receiving device. Furthermore, the at least one additional receiving device can generate an additional induced electric output voltage. The first inductive element of the at least one additional receiving device can e.g. be provided by or comprise an additional secondary-sided winding structure.

The circuit arrangement further comprises an additional rectifier for rectifying the additional induced electric output voltage of the first inductive element of the at least one additional receiving device. The additional rectifier is electrically connected to the first inductive element of the at least one additional receiving device.

The first receiving device and the at least one additional receiving device therefore provide an extended vehicle-sided receiving device. The receiving devices can be designed as separate units.

The circuit arrangement further comprises at least one switching element, wherein the at least one switching element is arranged within the circuit arrangement such that in a first switching state of the switching element a resulting output voltage of the circuit arrangement corresponds to the output voltage of the first rectifier and that in another switching state of the switching element, the resulting output voltage of the circuit arrangement corresponds to the output voltage of the additional rectifier.

The inductive elements are arranged on an AC part of the circuit arrangement, wherein the resulting output voltage is provided by a DC part of the circuit arrangement, wherein the rectifiers connect the AC part with the DC part. The switching element can be arranged within the DC part of the circuit arrangement.

The first inductive element of the first receiving device and the first inductive element of the additional receiving device can be provided by separate elements, which are, in a disconnected state, isolated from each other.

The resulting output voltage is a voltage which can be provided to a DC bus of the vehicle. In particular, the switching element can be arranged within an electrical connection of the rectifiers at the DC part of the rectifiers.

The first inductive element of the first receiving device and the first inductive element of the at least one additional receiving device can be designed such that if the same electromagnetic field is received, the voltage level of the output voltage of the first rectifier is different from the voltage level of the output voltage of the additional rectifier. In particular, the voltage level of the output voltage of the additional rectifier can be higher than the voltage level of the output voltage of the first rectifier.

The rectifiers and the switching element are arranged with respect to output terminals of the proposed circuit arrangement such that, depending on the switching state of the switching element, either the output voltage of the first rectifier or the output voltage of the additional rectifier is provided to said output terminals.

By controlling the switching states of the switching element, the resulting output voltage of the vehicle-sided circuit arrangement can be varied, in particular it can be changed from a first voltage level to another voltage level which is different from the first voltage level. This

advantageously allows regulating the resulting DC output voltage of the circuit arrangement such that voltage variations caused by variations in the primary current of the primary winding structure and/or voltage variations generated by variations of the mechanical clearance between the primary winding structure and the secondary winding structure can be compensated for. If e.g. the mechanical clearance increases and, in turn, the output voltage of the first rectifier decreases, the switching element can be controlled such that the resulting output voltage is switched to the output voltage of the additional rectifier which is higher than the output voltage of the first rectifier. Thus, the decrease of the resulting output voltage due to the increase of the mechanical clearance can be compensated.

In another embodiment, the first inductive element of the additional receiving device is electrically connected to a current path of the circuit arrangement which connects the first inductive element of the first receiving device and the first rectifier. In this case, a connecting point which is arranged within the current path connecting the first inductive element of the first receiving device and the first rectifier can be defined, wherein the first inductive element of the additional receiving device is electrically connected to said connecting point. This means that the connecting point is a branching point, wherein a first branch connects the connecting point to the first rectifier and another branch connects the connecting point to the first inductive element of the additional receiving device or comprises at least the first inductive element of the additional receiving device.

An alternating electromagnetic field is received by the first inductive element of the first receiving device and the first inductive element of the additional receiving device. If the switching element is, for example, operated in the first switching state, the DC output voltage of the circuit arrangement corresponds to the output voltage of the first rectifier which rectifies the AC output voltage of the first inductive element of the first receiving device. By electrically connecting the first inductive element of the additional receiving device to the first inductive element of the first receiving device via the connecting point, the additional rectifier rectifies the sum of the AC output voltages of the two inductive elements.

If the switching element is operated, for example, in the other switching state, the DC output voltage of the circuit arrangement corresponds to the output voltage of the additional rectifier and can therefore be higher than in the case that the switching element is operated in the first switching state.

This advantageously decreases costs and space requirements for providing the proposed circuit arrangement.

In another embodiment, the first inductive element of the first receiving device is provided by a first winding structure with a predetermined number of turns. The first inductive element of the additional receiving device is provided by an additional winding structure with a predetermined number of turns, wherein the number of turns of the first winding structure and the additional winding structure are different.

If the additional winding structure is not electrically connected to the first winding structure, e.g. not connected to the previously mentioned connecting point, and the output voltage of the additional rectifier is required to be higher than the output voltage of the first rectifier, the layout, e.g. the geometry and/or dimensions, and/or the number of turns of the additional winding structure are to be chosen such that a voltage induced by the alternating electromagnetic field in the additional winding structure is higher than the voltage induced by the alternating electromagnetic field in the first winding structure. If, for instance, the layout of both winding structures, e.g. the geometry of the winding structures or turns is similar, the number of turns of the additional winding structure should be chosen higher than the number of turns of the first winding structure. It is, of course, possible to provide a higher output voltage of the additional rectifier by alternatively or additionally varying the layout, e.g. the geometry, of the winding structure or turns of the additional winding structure.

In case that the additional winding structure is electrically connected to a current path of the circuit arrangement which electrically connects the first winding structure of the first receiving device to the first rectifier, and the output voltage of the additional rectifier is required to be higher than the output voltage of the first rectifier, the layout, e.g. the geometry and/or dimensions, and/or the number of turns of the additional winding structure can be chosen such that a voltage induced by the alternating electromagnetic field in the additional winding structure is lower than, equal to, or higher than the voltage induced by the alternating electromagnetic field in the first winding structure as the aforementioned conditions are always met. If, for instance, the layout of the winding structure, e.g. the geometry of the winding structure or turns is similar, the number of turns of the additional winding structure can be chosen lower than, equal to or higher than the number of turns of the first winding structure. Preferably, the number of turns of the

additional winding structure is smaller than the number of turns of the first winding structure if the additional winding structure is connected to a current path of the circuit arrangement which electrically connects the first winding structure of the first receiving device to the first rectifier.

As mentioned before, this allows providing a circuit arrangement which is able to generate two different DC voltage levels with reduced costs and space requirements, in particular for the additional winding structure.

In another embodiment, a compensating capacitive element is connected in series to the first inductive element of the first receiving device and/or a compensating capacitive element is connected in series to the first inductive element of the additional receiving device. The compensating capacitance can e.g. be provided by one or more compensating capacitor(s). The resulting impedance of the respective receiving device(s) can therefore be provided by the inductive element and the compensating capacitance. In particular, the compensating capacitance can be chosen such that the circuit arrangement is tuned. In this case, a resonant frequency of the resonant circuit provided by the proposed circuit arrangement is equal to a predetermined operating frequency of the inductive power transfer which can e.g. be 20 kHz.

In another embodiment, an output capacitive element is connected to output terminals of the first rectifier and/or an output capacitive element is connected to output terminals of the additional rectifier. Each rectifier can have two output terminals, wherein the aforementioned output voltage of the respective rectifier falls across these two output terminals. The said output capacitive element(s) is/are arranged on the DC part of the circuit arrangement.

These output capacitive elements advantageously provide an energy reservoir for providing energy when a load suddenly increases. This, in turn, prevents from operating states in which insufficient energy is provided by the circuit arrangement. Also, these output capacitive elements advantageously provide an energy reservoir for absorbing energy when a load suddenly decreases. This, in turn, prevents from operating states in which an overvoltage is provided by the circuit arrangement. Another function of the output capacitive elements is providing a current path for AC components of the output currents of the rectifier(s).

In another embodiment, a first output terminal of the first rectifier is connected to a first output terminal of the additional rectifier by a connecting current path, wherein the switching element is arranged within the connecting current path. In this case, the connecting current path comprises the switching element. The switching element can be e.g. an IGBT, a MOSFET or any other device capable of switching a current flow on or off. The switching element can have a conducting direction which can be oriented from the first output terminal of the additional rectifier towards the first output terminal of the first rectifier. In this case, a freewheeling diode can be connected antiparallel to the switching element.

This advantageously provides a simple and easy to realize connection or arrangement of the switching element on the DC part of the circuit arrangement.

In another embodiment, a parallel connection of a diode and an inductive element is arranged within the connecting current path, wherein the parallel connection is connected in series to the switching element. In this case, the connecting current path further comprises the parallel connection of the diode and the inductive element, wherein the parallel connection is connected in series to the switching element. This advantageously provides a current flow path if the switching element is switched off.

In another embodiment, a second output terminal of the first rectifier is connected directly to a second output terminal of the additional rectifier. This also advantageously allows a simple electrical connection of elements of the proposed circuit arrangements.

In a preferred embodiment, the circuit arrangement comprises three phases, wherein a first phase line of the first receiving device comprises the first inductive element of the first receiving device. A second phase line of the first receiving device comprises a second inductive element of the first receiving device and a third phase line of the first receiving device comprises a third inductive element of the first receiving device. Each phase line is connected to the first rectifier.

A first phase line of the additional receiving device comprises the first inductive element of the additional receiving device. A second phase line of the additional receiving device comprises a second inductive element of the additional receiving device and a third phase

line of the additional receiving device comprises a third inductive element of the additional receiving device. Each phase line of the additional receiving device is connected to the additional rectifier. In this case, the first rectifier and/or the additional rectifier can be provided by three-phase rectifiers, in particular three-phase diode rectifiers.

As previously described, the first phase line of the additional receiving device can be electrically connected to the first phase line of the first receiving device such that the first inductive element of the additional receiving device is connected to a current path which connects the first inductive element of the first receiving device to the first rectifier. Correspondingly, the second phase line of the additional receiving device and the third phase line of the additional receiving device can be connected to the second phase line and third phase line of the first receiving device respectively.

Further proposed is a method of operating a circuit arrangement, in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle. The circuit arrangement is designed according to one of the previously described embodiments.

According to the invention, switching states of the switching element of the circuit arrangement are controlled such that the resulting output voltage of the circuit arrangement corresponds either to the output voltage of the first rectifier or to the output voltage of the additional rectifier.

This advantageously allows a simple control of the circuit arrangement in order to provide a desired DC output voltage of the circuit arrangement.

In another embodiment, the switching element is controlled depending on the resulting DC output voltage. This advantageously allows controlling the switching element depending on a vehicle-sided signal, in particular the voltage level of the resulting DC output voltage.

In another embodiment, a first switching state is activated if the resulting output voltage exceeds or reaches a first predetermined voltage level. A second switching state is activated if the resulting output voltage falls below or reaches a second predetermined voltage level. The first predetermined voltage level is higher than the second predetermined voltage level. In this case, the output voltage provided by the additional rectifier is higher than the output voltage provided by the first rectifier.

This advantageously provides a simple control scheme, in particular a threshold-based control scheme.

In another embodiment, the first switching state is activated if the resulting output voltage exceeds or reaches a first predetermined voltage level and an actual switching state corresponds to the second switching state. The second switching state is activated if the resulting output voltage falls below or reaches a second predetermined voltage level and the actual switching state corresponds to the first switching state. In this case, a hysteresis window is provided by the proposed control scheme. This advantageously allows avoiding unwanted oscillations of the resulting output voltage.

In another embodiment, a switching operation is performed as a zero current switching. In case of a zero current switching operation, another switching state of the switching element is activated when a current flowing through the switching element is zero or nearly zero. The transition of the switching states can e.g. be executed with zero current switching due to the inductive element of the previously described parallel connection. This zero current switching significantly reduces the turn-on switching losses.

This advantageously reduces an energy loss due to switching operations.

Further proposed is a method of manufacturing a circuit arrangement, in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle, comprising the steps of:

- providing at least a first inductive element of a first receiving device for receiving an alternating electromagnetic field and to generate a first induced electric output voltage,
- providing a first rectifier for rectifying the first induced electric output voltage,
- connecting the first inductive element to the first rectifier,
- providing at least a first inductive element of at least one additional receiving device for receiving the alternating electromagnetic field and to generate an additional induced electric output voltage,
- providing an additional rectifier for rectifying the additional induced electric output voltage,

- connecting the first inductive element of the additional receiving device to the additional rectifier,
- providing at least one switching element,
- arranging the at least one switching element within the circuit arrangement such that in a first switching state of the switching element a resulting output voltage of the circuit arrangement corresponds to the output voltage of the first rectifier and that in another switching state of the switching element, the resulting output voltage of the circuit arrangement corresponds to the output voltage of the additional rectifier.

This advantageously allows providing a circuit arrangement which is able to generate a resulting DC output voltage with two different voltage levels.

In another embodiment, the method further comprises the step of electrically connecting the first inductive element of the additional receiving device to a current path of the circuit arrangement which electrically connects the first inductive element of the first receiving device and the first rectifier.

This advantageously allows manufacturing the proposed circuit arrangement with reduced costs and space requirements, since the inductive element which generates the AC voltage which is rectified by the additional rectifier is provided by the first inductive element of the first receiving device and the first inductive element of the additional receiving device.

In another embodiment, the method further comprises the step of connecting a first output terminal of the first rectifier to a first output terminal of the additional rectifier by a connecting current path, wherein the connecting current path comprises the switching element.

This advantageously allows a simple electrical set up the proposed circuit arrangement.

Further proposed is a vehicle, wherein the vehicle comprises a circuit arrangement according to one of the previously described embodiments.

Examples of the invention will be described with reference to the attached figures in the following:

- Fig. 1 a schematic circuit diagram of a system for inductive power transfer to the vehicle according to the state of the art,
- Fig. 2 a schematic circuit diagram of a vehicle-sided circuit arrangement according to the invention,
- Fig. 3a an exemplary time course of a gate signal of a switching element,
- Fig. 3b an exemplary time course of a resulting output voltage of the circuit arrangement,
- Fig. 3c an exemplary time course of an output voltage of an additional rectifier,
- Fig. 3d an exemplary time course of a voltage falling across a switching element,
- Fig. 3e an exemplary time course of currents flowing through a diode and a limiting inductor,
- Fig. 4 a schematic control scheme for switching states of a switching element, and
- Fig. 5 a schematic circuit diagram of another vehicle-sided circuit arrangement according to the invention.

Fig. 1 shows a schematic circuit diagram of a wayside circuit arrangement 10 and a vehicle-sided circuit arrangement 11 according to the state of the art. The wayside circuit arrangement 10 comprises different segments N, which are arranged along a path of travel of a vehicle travelling on a driving surface of a route. In Fig. 1, only one segment N is shown. Each segment N comprises an inverter 12, a filter circuit 13 and primary windings 14. The inverter 12 is connected via a capacitor 15 to a power line 16 which is fed by a voltage source (not shown).

The vehicle-sided circuit arrangement 11 comprises a first receiving device 2. The first receiving device 2 comprises a first winding structure L1_1, a second winding structure L2_1 and a third winding structure L3_1 for receiving an alternating electromagnetic field generated by the primary windings 14 and for generating AC electric output voltages.

Furthermore, the receiving device 2 comprises a first capacitor C1_1, which is connected in series to the first winding structure L1_1. Furthermore, the first receiving device 2 comprises a second capacitor C2_1 and a third capacitor C3_1, which are connected to the second winding structure L2_1 and the third winding structure L3_1 of the first receiving device 2 respectively. The series connection of the first winding structure L1_1

and the first capacitor C1_1 is arranged in a first phase line. Correspondingly, the series connections of the remaining winding structures L2_1, L3_1 and the remaining capacitors C2_1, C3_1 are arranged in a second and a third phase line, respectively. The capacitors C1_1, C2_1, C3_1 provide compensating capacitors. The three phase lines are connected to a first rectifier 3 which is provided by a diode rectifier. The first rectifier 3 connects the three-phase AC part of the circuit arrangement 11 to a DC part of the circuit arrangement 11. A circuit capacitor 4 is connected to output terminals 3a, 3b of the first rectifier 3. Across the circuit capacitor 4, an (unfiltered) output voltage V_{out} of the circuit arrangement 11 is provided.

Furthermore, a radio frequency filter 5 is connected to the circuit capacitor 4. A filtered output voltage falls across output terminals 11a, 11b of the vehicle-sided circuit arrangement 11. Shown is also a load 6 which is connected to the output terminals 11a, 11b of the vehicle-sided circuit arrangement 11.

In Fig. 2, a schematic circuit arrangement 11 according to the invention is shown. In contrast to the circuit arrangement 11 shown in Fig. 1, the vehicle-sided circuit arrangement 11 comprises an additional receiving device 7 for receiving the previously described alternating electromagnetic field generated by the primary winding structure 14 (see Fig. 1). The additional receiving device 7 comprises a first winding structure L1_2, a second winding structure L2_2 and third winding structure L3_2. The first winding structure L1_2 is connected in series to a first capacitor C1_2 of the additional receiving device 7. Correspondingly, the second winding structure L2_2 and the third winding structure L3_2 are connected to capacitors C2_2, C3_2 of the additional receiving device 7.

The series connection of the first winding structure L1_2 and the first capacitor C1_2 of the additional receiving device 7 are arranged in a first phase line of the additional receiving device 7 which is electrically connected to a current path of the circuit arrangement 11, wherein this current path electrically connects the series connection of the first winding structure L1_1 and the first capacitor C1_1 of the first receiving device 2 to the first rectifier 3. The series connection of the second winding structure L2_2 and the second capacitor C2_2 of the additional receiving device 7 is arranged in a second phase line of the additional receiving device 7 and is electrically connected to a current path of the circuit arrangement 11, wherein this current path electrically connects the series connection of the second winding structure L2_1 and the second capacitor C2_1 of the

first receiving device 2 to the first rectifier 3. The series connection of the third winding structure L3_2 and the third capacitor C3_2 is arranged in a third phase line of the additional receiving device 7 and is electrically connected to a current path of the circuit arrangement 11, wherein this current path electrically connects the series connection of the third winding structure L3_1 and the third capacitor C3_1 of the first receiving device 2 to the first rectifier 3. Thus, in each current path connecting the series connection of the winding structures L1_1, L2_1, L3_1 and the respective capacitors C1_1, C2_1, C3_1 of the first receiving device 2, a connecting point is provided at which the current path is branched into two branches. A first branch is connected to the first rectifier 3 and a second branch is connected to an additional rectifier 8, wherein the series connection of the winding structures L1_2, L2_2, L3_2 and the respective capacitors C1_2, C2_2, C3_2 of the additional receiving device 7 are arranged within the second branch.

The vehicle-sided circuit arrangement 11 comprises the additional rectifier 8 for rectifying the AC voltages induced within the winding structures L1_2, L2_2, L3_2 of the additional receiving device 7. All phase lines of the additional receiving device 7 are connected to the additional rectifier 8.

The circuit arrangement 11 further comprises a switching element S which is provided by an IGBT. The switching element S has a conducting direction which is symbolized by an arrow 17. A freewheeling diode DS is connected antiparallel to the switching element S.

Furthermore, the circuit arrangement 11 comprises a limiting inductor L and a diode D1 connected in parallel with the limiting inductor L. The switching element S is connected in series to the parallel connection of the limiting inductor L and the diode D1. The said series connection is arranged in a connecting current path of a first output terminal 8a of the additional rectifier 8 and a first output terminal 3a of the first rectifier 3.

An additional circuit capacitor 9 is connected to output terminals 8a, 8b of the additional rectifier. A second terminal 8b of the additional rectifier 8 is connected to a second terminal 3b of the first rectifier 3 by a current path which does not comprise further elements (direct connection). Also shown is a radio frequency filter 5 by which an output voltage V_{out} of the shown circuit arrangement 11 is filtered.

Furthermore shown is a control unit 18 which generates a gate signal for the switching element S.

The additional rectifier 8 can have the same ratings as the first rectifier 3. The winding structures L1_2, L2_2, L3_2 of the additional receiving device 7 have a fewer number of turns than the winding structures L1_1, L2_1, L3_1 of the first receiving device 2. If the switching element S is off (which corresponds to a first switching state of the switching element S), the aforementioned connecting current path is interrupted. The output voltage V_{out} corresponds to an output voltage V_3 of the first rectifier 3. If the switching element is on (which corresponds to another switching state of the switching element S), the connecting current path is not interrupted. In this case, the output voltage V_{out} corresponds to an output voltage V_8 of the additional rectifier 8.

Because of the electrical connection of the phase lines of the first receiving device 2 and the additional receiving device 7, the DC output voltage V_8 of the additional rectifier 8 will be higher than the output voltage V_3 of the first rectifier 3. By connecting the additional winding structures L1_2, L2_2, L3_2 of the additional receiving device 7 to the current paths which connect the winding structures L1_1, L2_1, L3_1 of the first receiving device 2 to the first rectifier 3, the total number of windings in each phase line is increased, which, in turn, increases the output voltage V_8 of the additional rectifier 8 in comparison to the output voltage V_3 of the first rectifier 3. It is of course possible to have more than one additional receiving device 7, wherein phase lines of these additional receiving devices can be either connected to the phase lines of the first receiving device 2 or to the phase lines of the shown additional receiving device 7. If the switching element is switched off (first switching state), phase currents in the phase lines of the additional receiving device 7 will be zero as there is no path for these currents to flow.

Fig. 3a shows an exemplary time course of a gate signal GS of the switching element S (see Fig. 2). Fig. 3b shows an exemplary time course of a resulting output voltage V_{out} of the circuit arrangement 11 (see Fig. 2). Fig. 3c shows an exemplary time course of an output voltage V_8 of the additional rectifier 8 (see Fig. 2). Fig. 3d shows an exemplary time course of a voltage V_s falling across the switching element S (see Fig. 2). Fig. 3e shows an exemplary time course of currents I_D , I_L flowing through the diode D1 and the limiting inductor L.

At a first switching time instant t_1 , a gate signal GS provided by the control unit 18 (see Fig. 2) is changed from a low level signal LLS to a high level signal HLS. Thus, the switching state of the switching element S is changed from the first switching state (off) to another switching state (on). At a second switching instant t_2 , the gate signal GS is changed from the high level signal HLS to the low level signal LLS. Thus, the switching element S is switched off (switched to the first switching state).

In Fig. 3b, a time course of the output voltage V_{out} is shown. When the switching element S is in the first switching state and a steady-state condition is achieved, the current paths provided by the phase lines of the additional receiving device 7 are opened for positive values of the phase currents flowing within these phase lines of the additional receiving device 7. However, the said current paths are closed for negative values of said phase currents. In this case, a phase current is considered a positive phase current if the phase current direction is oriented towards the additional rectifier 8. Therefore, the capacitors C1_2, C2_2, C3_2 of the additional receiving device 7 are charged with a DC voltage which is equal to the peak value of the voltage induced in the winding structures L1_2, L2_2, L3_2 of the additional receiving device 7. In a steady-state condition, the phase currents in the additional receiving device 7 are zero and the capacitors C1_2, C2_2, C3_2 keep the said DC voltage level because there is no path for a discharging current flow.

This results in a high output voltage V_8 of the additional rectifier 8 if the switching element is off (first switching state). If switching element S is turned on at the first time instant t_1 , there is a bidirectional current path provided by the phase lines of the additional receiving device 7. The energy stored in the capacitors C1_2, C2_2, C3_2 of the additional receiving device 7 is discharged to the DC part of the circuit arrangement 11. At this time, the output voltage V_8 of the additional rectifier 8, which is shown in Fig. 3c, drops from the peak value to an average value of the rectified voltage which is induced within the winding structures L1_1, L2_1, L3_1, L1_2, L2_2, L3_2 respectively. The effective DC voltage across the capacitors C1_2, C2_2, C3_2 of the additional receiving device 7 reaches zero.

In Fig. 3c it is shown, that a voltage oscillation occurs after the first switching time instant t_1 . However, this oscillation takes a very short time and disappears in a steady-state condition. If the switching element S is switched off again at the second switching time

instant t_2 , energy stored in the limiting inductor L is discharged by a current I_D flowing through the diode $D1$. Also, energy stored in leakage inductances of the winding structures $L1\_2$, $L2\_2$, $L3\_2$ of the additional receiving device 7 is transferred to the capacitors $C1\_2$, $C2\_2$, $C3\_2$ and thus charges said capacitors $C1\_2$, $C2\_2$, $C3\_2$. This generates oscillations of the output voltage V_{out} after the second switching time instant t_2 (see Fig. 3b) and oscillations of a voltage V_S falling across terminals of the switching element S after the second switching time instant t_2 (see Fig. 3d). It can be seen that the output voltage V_{out} stabilizes at an average value of the rectified voltages which are induced exclusively within the winding structures $L1\_1$, $L2\_1$, $L3\_1$ of the first receiving device 2 after the second switching time instant t_2 .

Referring to Fig. 3e, a time course of a current I_L through the limiting inductor L and a time course of a current I_D through the diode $D1$ is shown. After the second switching time instant t_2 , an energy stored in the limiting inductor L keeps the current I_L through the limiting inductor L flowing. This current I_L through the limiting inductor L charges an inherent emitter-collector capacitance inside the switching element S and therefore, a collector voltage increases. If the collector voltage exceeds the output voltage V_S of the additional rectifier 8, the diode $D1$ is biased in forward mode and starts conducting. The voltage falling across the diode $D1$ is constant so that the currents I_L , I_D drop in a linear fashion until they reach zero.

In the circuit arrangement 11 shown in Fig. 2, the output voltage V_{out} of the circuit arrangement 11 will be higher than the peak values of the voltages between the phase lines of the first receiving device 2 if the switching element is turned on. In this case, the diodes of the diode rectifier 3 do not conduct any current. Thus, the resulting output voltage V_{out} is equal to the output voltage V_S of the additional rectifier 8 while no current flows through the first rectifier 3.

Fig. 4 shows a schematic control scheme of a switching element S shown in Fig. 2. It is shown that the switching state of the switching element S is controlled depending on a voltage level of an output voltage V_{out} of the circuit arrangement 11. A first switching state is activated, if the resulting output voltage V_{out} exceeds or reaches a first predetermined voltage level $V1$ and an actual switching state corresponds to the second switching state in which a high level signal HLS supplied as a gate signal GS (see Fig. 3a). The second switching state is activated if the resulting output voltage V_{out} falls below or reaches a

second predetermined voltage level V2 and the actual switching state corresponds to the first switching state which is achieved if a low level signal LLS is applied as a gate signal GS.

The first predetermined voltage level V1 is higher than the second predetermined voltage level V2 which provides a large hysteresis window.

The proposed circuit arrangement 11 offers a number of advantages. The proposed circuit arrangement 11 increases the output voltage level and thus decreases an AC current level which directly reduces unwanted emissions out of the vehicle which comprises the proposed circuit arrangement 11. The additional elements, namely the additional winding structures L1_2, L2_2, L3_2, the capacitors C1_2, C2_2, C3_2, the additional rectifier 8, the switching element S, the additional circuit capacitor 9, the limiting inductor L and the diode D1 can be connected in parallel with the original design shown in Fig. 1. It is therefore possible to install the proposed circuit arrangement 11 on existing circuit arrangements according to the state of the art.

Another advantage is that only one switching element S is needed. This reduces the number of drive circuits and costs of the system. In particular, there is no "switch leg" which is defined as a vertical branch of two switches in series between two DC levels. Therefore, there is no possibility of unwanted short circuits due to a noise or failure in the control signal of the switching elements. This is a major concern in half or full bridge arrangements.

Furthermore, the switching element S is connected between two high level output terminals 3a, 8a. Therefore, its highest voltage stress is smaller than a maximum output DC level of the additional rectifier 8 (with respect to the reference potential provided by the second terminal 8b). The switching element S, in this case the IGBT, can be selected from standard commercial off-the-shelf switch module products. Due to having the limiting inductor L in series with the switching element S, the switching element S can be switched on with a so-called zero current switching which reduces switching losses. The limiting inductor L also reduces the rate of current variation in the switching element S, which eliminates emissions due to rapid current changes in the switching element. Furthermore, there is no limit on selecting the switching time instants t1, t2 of the switching element S. This simplifies the control and increases the reliability of the circuit arrangement 11. The

diode D1 protects the switching element S from high voltage stress. The diode D1 is a standard off-the-shelf item and does not need to be a very high speed and expensive element.

Although there are two rectifiers 3, 8 in the circuit arrangement 11, these rectifiers 3, 8 will never work at the same time. When the switching element S is switched off, only the first rectifier 3 will conduct current and when the switching element S is switched on, only the additional rectifier 8 will conduct current. Thus, the current does not flow through both rectifiers 3, 8 and the power loss will not be doubled. Due to having AC capacitors C1_2, C2_2, C3_2 in series with the winding structures L1_2, L2_2, L3_2 of the additional receiving device 7, there is no possibility of having a steady-state DC current flow through these winding structures L1_2, L2_2, L3_2. Therefore, there is no possibility of a saturation of a ferrite core of the previously described extended receiving device saturation due to such DC currents. The additional rectifier 8 can be similar to the first rectifier 3 and thus does not add complexity during manufacturing of the circuit arrangement 11.

No extra sensor elements are required and controlling the circuit arrangement 11 can be done by using signal from existing sensor elements.

In the case of any failure in the added elements, the first rectifier 3 is able to operate and feed elements of the DC bus of the vehicle, e.g. an electric machine, with slightly lower performance. Therefore, the circuit arrangement 11 will be capable of providing power to the electric machine which, in turn, allows e.g. a tram to reach a maintenance facility with no interruption in service.

The circuit arrangement 11 only used vehicle-sided signals to operate. Therefore, there is no need to have any signal transfer or communication to the wayside structure 10. This provides more reliability and exclusion of any interference in such communication systems in the loop.

Furthermore, no complicated control scheme for controlling the switching time instants t_1 , t_2 is required. A very simple controller can implement the scheme shown in Fig. 4.

The control unit 18 of the system can be fully vehicle-sided controller which can be integrated with the existing controllers of other systems of the vehicle such as the propulsion controller. The entire system can act as a more intelligent unity. Furthermore, no calibration or adjustment is necessary.

In Fig. 5, a schematic circuit diagram of another arrangement 11 according to the invention is shown. In contrast to the circuit arrangement 11 shown in Fig. 2, the series connections of the winding structures L1_1, L2_1, L3_1 and the capacitors C1_1, C2_1, C3_1 of the first receiving device 2 are not electrically connected to the series connections of the winding structures L1_2, L2_2, L3_2 and the capacitors C2_1, C2_2, C3_2 of the additional receiving device 7. Hence, the current paths connecting the series connections of the winding structures L1_1, L2_1, L3_1 and the capacitors C1_1, C2_1, C3_1 of the first receiving device 2 with the first rectifier 3 do not branch.

If the desired output voltage V_8 of the additional rectifier 8 is required to be lower or higher than the output voltage V_3 of the first rectifier 3 under the same operating conditions, e.g. if the same alternating electromagnetic field is applied, the winding structures L1_2, L2_2, L3_2 of the additional receiving device 7 have to be designed such that the desired output voltage V_8 of the additional rectifier 8 is provided. For example, a number of turns of the winding structures L1_2, L2_2, L3_2 of the additional receiving device 7 can be chosen smaller or higher than a number of turns of the winding structures L1_1, L2_1, L3_1 of the first receiving device 7.

Claims

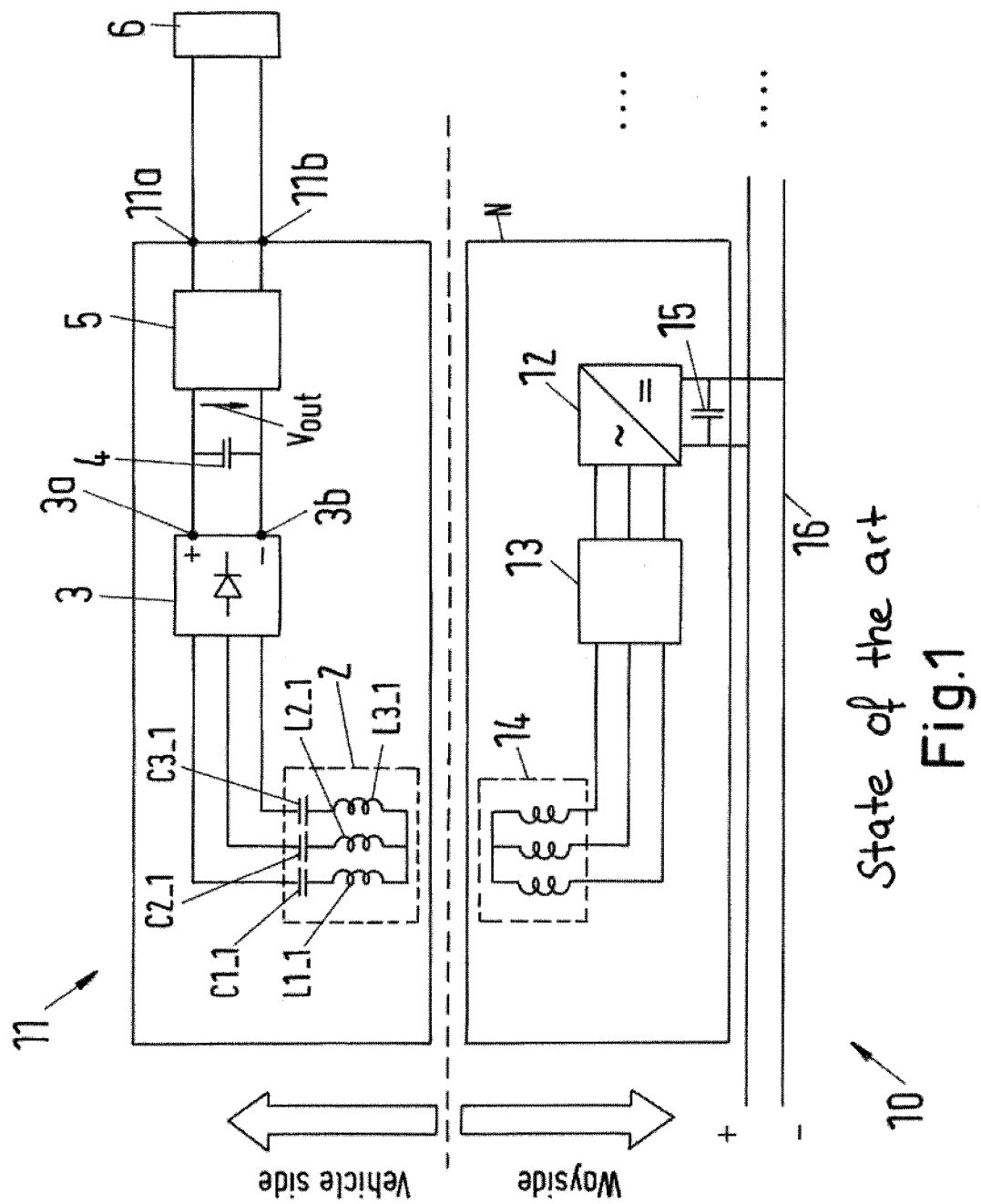
1. Circuit arrangement, in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle,
wherein the circuit arrangement (11) comprises a first inductive element of a first receiving device (2) for receiving an alternating electromagnetic field and to generate a first induced electric output voltage, wherein the circuit arrangement (11) further comprises a first rectifier (3) for rectifying the first induced electric output voltage, characterized in that
the circuit arrangement (11) comprises a first inductive element of at least one additional receiving device (7) for receiving the alternating electromagnetic field and to generate an additional induced electric output voltage, wherein the circuit arrangement (11) further comprises an additional rectifier (8) for rectifying the additional induced electric output voltage, wherein the circuit arrangement (11) further comprises at least one switching element (S), wherein the at least one switching element (S) is arranged within the circuit arrangement (11) such that in a first switching state of the switching element (S) a resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_3) of the first rectifier (3) and that in another switching state of the switching element (S) the resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_8) of the additional rectifier (8).
2. The circuit arrangement according to claim 1, wherein the first inductive element of the additional receiving device (7) is electrically connected to a current path of the circuit arrangement (11) which connects the first inductive element of the first receiving device (2) and the first rectifier (3).
3. The circuit arrangement according to one of the claims 1 or 2, wherein the first inductive element of the first receiving (2) device is provided by a first winding structure (L1_1) with a predetermined number of turns, wherein the first inductive element of the additional receiving device (7) is provided by an additional winding structure (L1_2) with a predetermined number of turns, wherein the number of turns of the winding structures (L1_1, L1_2) are different.

4. The circuit arrangement according to one of the claims 1 to 3, wherein a compensating capacitive element (C1_1) is connected in series to the first inductive element of the first receiving device (2) and/or a compensating capacitive element (C1_2) is connected in series to the first inductive element of the additional receiving device (7).
5. The circuit arrangement according to one of the claims 1 to 4, wherein an output capacitive element is connected to output terminals (3a, 3b) of the first rectifier (3) and/or an output capacitive element is connected to output terminals (8a, 8b) of the additional rectifier (8).
6. The circuit arrangement according to one of the claims 1 to 5, wherein a first output terminal (3a) of the first rectifier (3) is connected to a first output terminal (8a) of the additional rectifier (8) by a connecting current path, wherein the switching element (S) is arranged in the connecting current path.
7. The circuit arrangement according to claim 6, wherein a parallel connection of a diode (D1) and an inductive element (L) is arranged in the connecting current path, wherein the parallel connection is connected in series to the switching element (S).
8. The circuit arrangement according to one of the claims 1 to 7, wherein a second output terminal (3b) of the first rectifier (3) is connected directly to a second output terminal (8b) of the additional rectifier (8).
9. The circuit arrangement according to one of the claims 1 to 8, wherein the circuit arrangement (11) comprises three phases, wherein a first phase line of the first receiving device (2) comprises the first inductive element of the first receiving device (2), wherein a second phase line of the first receiving device (2) comprises a second inductive element of the first receiving device (2), wherein a third phase line of the first receiving device (2) comprises a third inductive element of the first receiving device (2), wherein each phase line is connected to the first rectifier (3), wherein a first phase line of the additional receiving device (7) comprises the first inductive element of the additional receiving device (7), wherein a second phase line of the additional receiving device (7) comprises a second inductive element of the additional receiving device (7), wherein a third phase line of the additional receiving device (7) comprises a third inductive element of the additional receiving device (7), wherein each phase line of the

additional receiving device (7) is connected to the additional rectifier (8).

10. A method of operating a circuit arrangement, in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle, according to one of the claims 1 to 9, characterized in that switching states of a switching element (S) are controlled such that the resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds either to the output voltage (V_3) of the first rectifier (3) or to the output voltage (V_8) of the additional rectifier (8).
11. The method of claim 10, wherein the switching states of the switching element (S) are controlled depending on the resulting output voltage (V_{out}).
12. The method of claim 11, wherein a first switching state is activated if the resulting output voltage (V_{out}) exceeds or reaches a first predetermined voltage level (V1), wherein another switching state is activated if the resulting output voltage (V_{out}) falls below or reaches a second predetermined voltage level (V2), wherein the first predetermined voltage level (V1) is higher than the second predetermined voltage level (V2).
13. The method of claim 12, wherein the first switching state is activated if the resulting output voltage (V_{out}) exceeds or reaches a first predetermined voltage level (V1) and an actual switching state corresponds to the other switching state, wherein the second switching state is activated if the resulting output voltage (V_{out}) falls below or reaches a second predetermined voltage level (V2) and the actual switching state corresponds to the first switching state.
14. The method of claim 13, wherein a switching operation is performed as a zero current switching.
15. A method of manufacturing a circuit arrangement (11), in particular a circuit arrangement of a vehicle for inductive power transfer to the vehicle, comprising the steps of:
 - providing at least a first inductive element of a first receiving device (2) for receiving an alternating electromagnetic field and to generate an first induced electric output voltage,

- providing a first rectifier (3) for rectifying the first induced electric output voltage,
 - connecting the first inductive element to the first rectifier (3),
 - providing at least a first inductive element of at least one additional receiving device (7) for receiving the alternating electromagnetic field and to generate an additional induced electric output voltage,
 - providing an additional rectifier (8) for rectifying the additional induced electric output voltage,
 - connecting the first inductive element of the additional receiving device (7) to the additional rectifier (8),
 - providing at least one switching element (S),
 - arranging the at least one switching element (S) within the circuit arrangement (11) such that in a first switching state of the switching element (S) a resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_3) of the first rectifier (3) and that in another switching state of the switching element (S), the resulting output voltage (V_{out}) of the circuit arrangement (11) corresponds to the output voltage (V_8) of the additional rectifier (8).
16. The method of claim 15, comprising the step of electrically connecting the first inductive element of the additional receiving device (7) to a current path of the circuit arrangement (11) which electrically connects the first inductive element of the first receiving device (2) and the first rectifier (3).
17. The method of claim 15 or 16, comprising the step of connecting a first output terminal (3a) of the first rectifier (3) to a first output terminal (8a) of the additional rectifier (8) by a connecting current path, wherein the switching element (S) is arranged in the connecting current path.
18. A vehicle, wherein the vehicle comprises a circuit arrangement according to one of the claims 1 to 9.



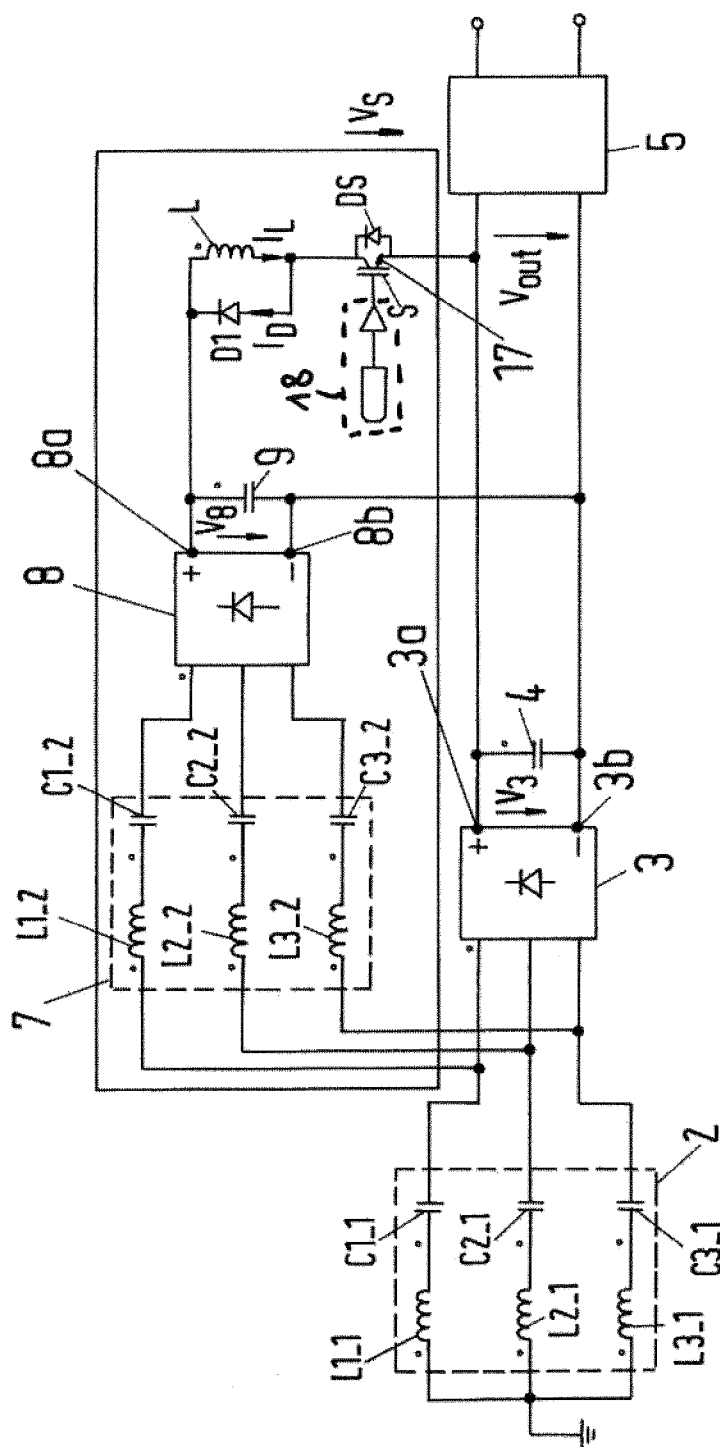


Fig.2

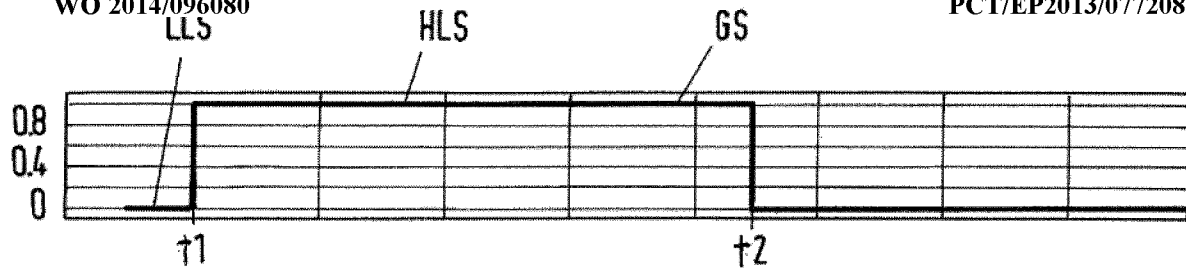


Fig.3a

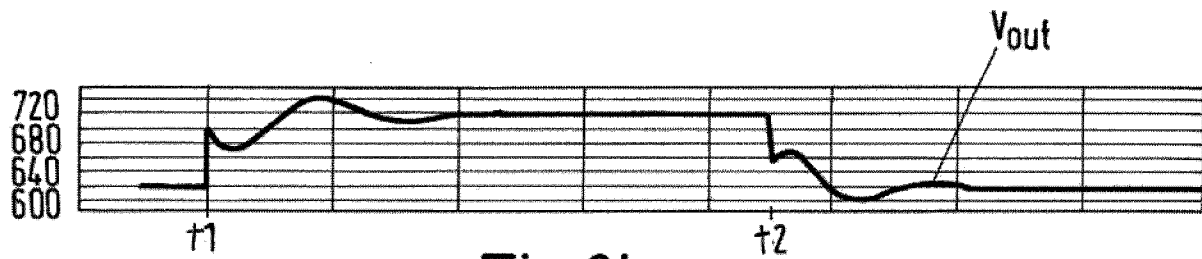


Fig.3b

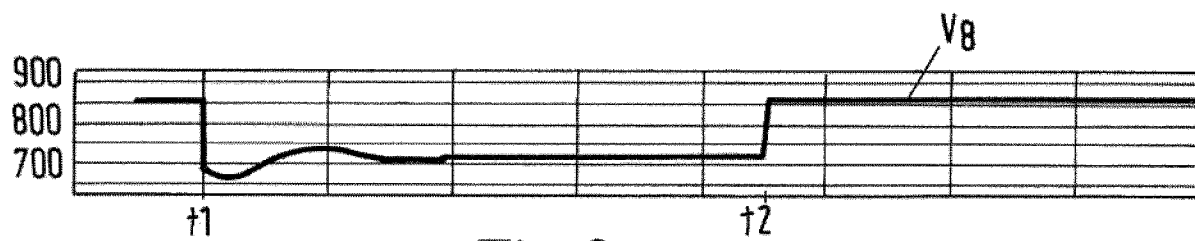


Fig.3c

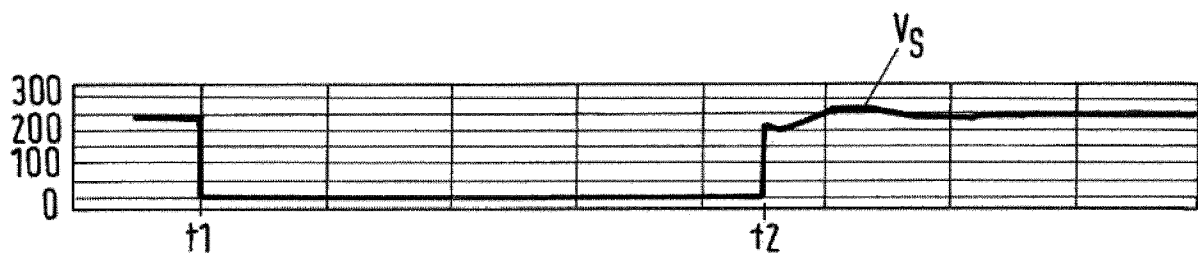


Fig.3d

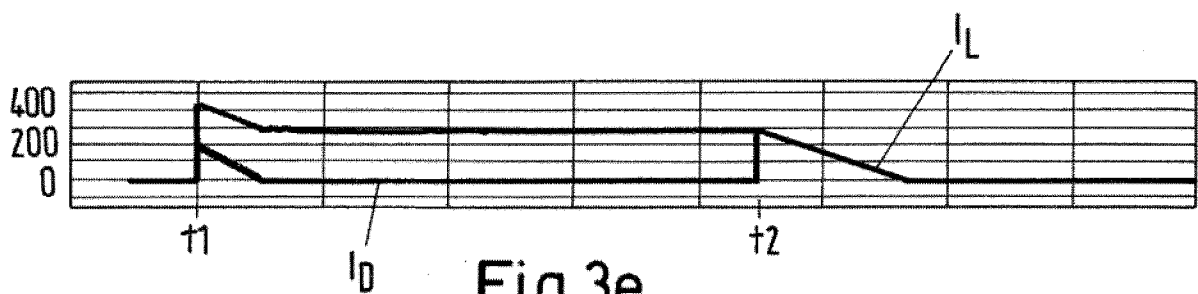


Fig.3e

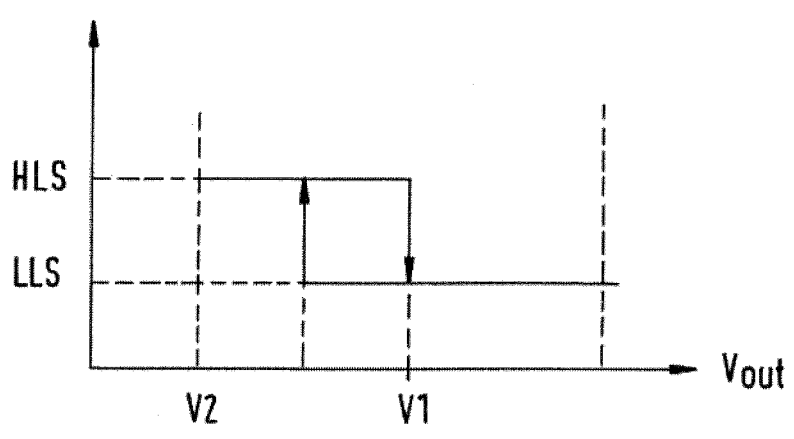


Fig.4

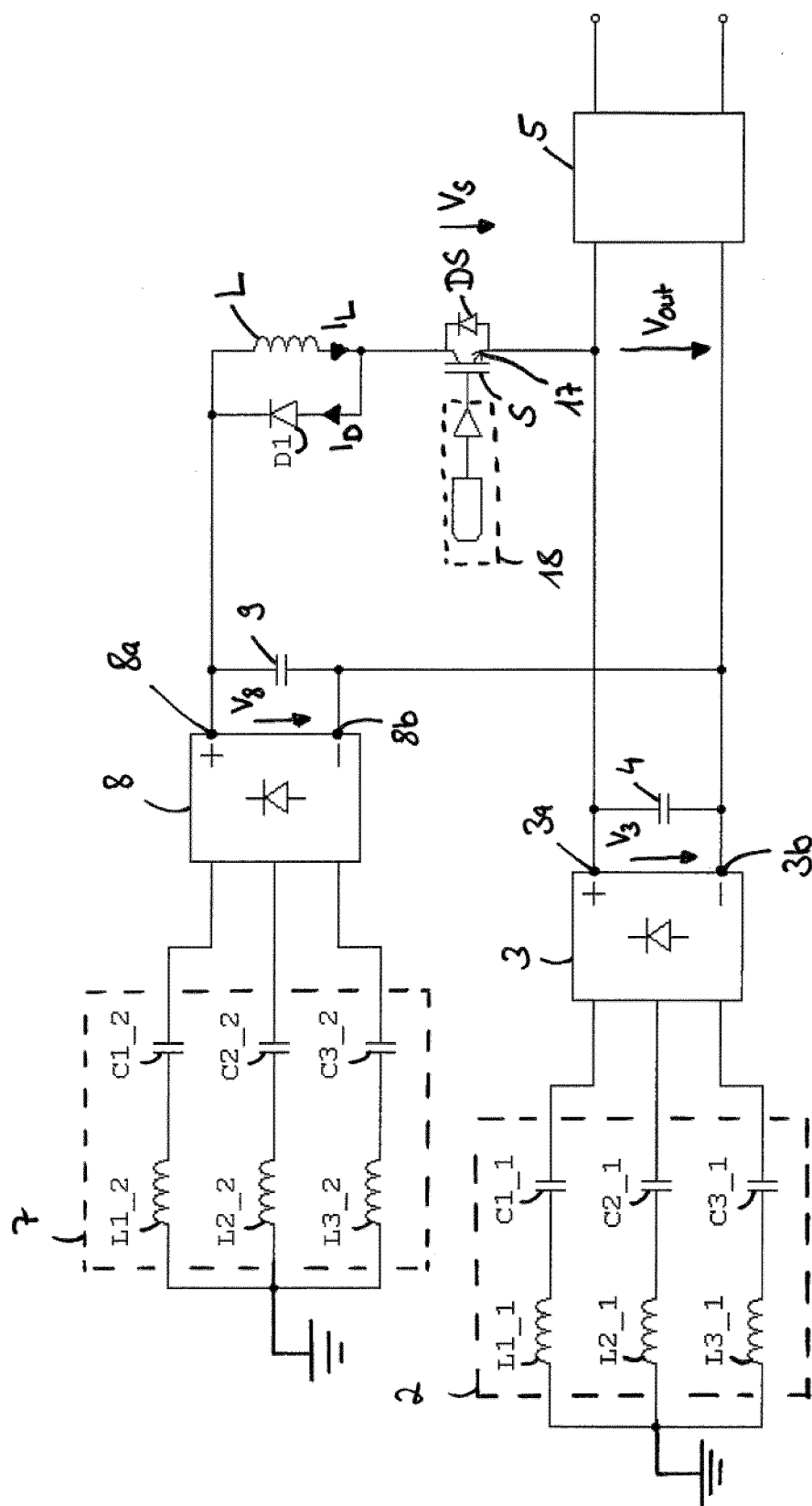


Fig. 5