Application of inverter parallel operation strategy in railway auxiliary converters

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***Abstract*— This paper describes the implementation of a control strategy for the parallel cooperation of inverters to railway auxiliary converters. The three-phase outputs of the parallel system of auxiliary converters are connected to a common bus. To ensure proper operation and load current sharing, droop-based algorithms are used to control the inverters. The proposed inverter control technique and strategy of inverter outputs and loads connection to a common bus was verified on a four auxiliary converters parallel system. The achieved current sharing in static and dynamic states of a parallel system is presented.**

Keywords*— *parallel operation, three phase inverter, auxiliary converter, droop control

I. Introduction

Railway auxiliary converters are static power converters that provide power to auxiliary loads such as heating, ventilation, air conditioning, lighting in passenger coaches, electric multiple units (EMU), trams and metros. They are powered by a high-voltage (HV) continuous train line. The auxiliary converter transforms this high voltage into a voltage with parameters suitable for supplying all the electrical appliances of the wagon. Manufacturers of auxiliary converters, strives to bring innovative solutions to this area. One such innovative approach is parallel cooperation. Parallel interconnection of the outputs of the auxiliary converters installed on the individual wagons of the train via a common line can bring some advantages. One of the main advantages is to increase the reliability and availability of such a system through active redundancy. This means, that if the individual inverters of the parallel system have a certain power reserve, the power supplied to the loads will not be interrupted in the event of a failure of one or more converters. The power of the loads connected to the common bus will be shared by the remaining working inverters. On the other hand, if the converters do not operate in parallel, the loads connected to the failed converter will not be powered. Another advantage is the better configurability and flexibility, which allows reduction the number of train converters. In case of sufficient power dimensioning of converters, they do not have to be installed on every wagon. As the loads are supplied from the common bus, the power consumption of the wagon without converter will be covered by the converters on the other wagons supplying power to the common bus.

The following section of the article introduces the hardware configuration of the parallel system of auxiliary converters and the procedure of creating a common network. Section III describes inverters power sharing principles and the block diagram of the inverter control strategy for parallel operation is shown. The experimental setup and the achieved results of the experiments are presented in section IV. The presented research and the achieved experimental results are summarized in section V.

II. Parallel System of Auxiliary Converters

Fig. 1 shows a simplified block diagram of the proposed train auxiliary power supplies parallel system. One auxiliary converter is located on each wagon. The high-voltage line runs across the whole train and connects all wagons to the HV. Power to HV train line is supplied by the separate winding of the traction transformer of the locomotive or by the overhead line. This voltage can be AC or DC and can be of various values (1000 to 3000V, AC or DC) depending on the type of traction supply system. Each auxiliary converter consists of two basic parts. From a high voltage input converter that converts the input DC or AC high voltage to a stabilized DC link voltage.

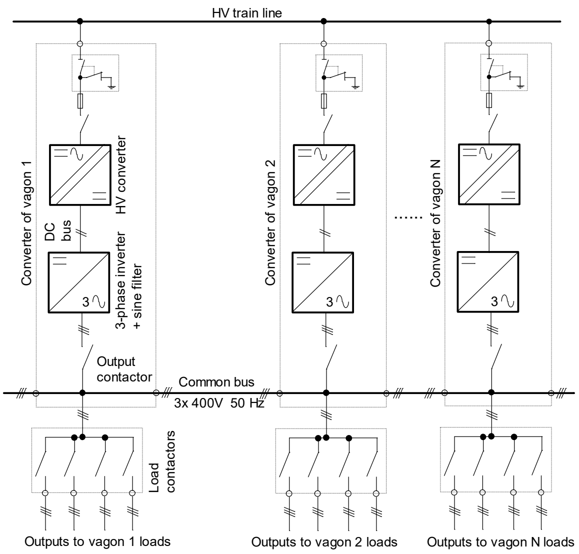

Fig. 1. Block diagram of a train auxiliary converters parallel system.

Each auxiliary converter consists of two basic parts. The first part is a high-voltage input converter, which converts the input DC or AC high voltage into a stabilized DC voltage and galvanically isolates the DC bus from the inverter input. In the case of AC voltage supplying, it provides power factor compensation and allows to achieve a sinusoidal shape of the input current with a low content of higher harmonics. In addition, there are input fuses, a disconnector, pre-charging circuits and an input contactor on the high-voltage side of the converter. The output part consists of a three-phase inverter module. The inverter is powered from the DC bus by a stabilized voltage, which converts it to an output three-phase AC voltage. To achieve low harmonic distortion, the inverter output voltage is filtered by a sine filter. In the parallel system shown in Fig. 1, the nominal voltage value in the common

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three-phase bus is 3 x 400 V 50 Hz. The network type is IT without a neutral. The inverters outputs are connected to the common three-phase bus of the train via contactors. This allows the inverter output to be isolated from the bus in the event of a fault and the system can continue to operate without interruption. The loads are also connected to a common three-phase line via contactors allowing the connection of train appliances after all inverters have been connected and the voltage on the common bus has stabilized.

A certain specified procedure must be followed to properly start a system of parallel operating inverters. In order to prevent inverter faults during transients when connecting to a common AC network, it is necessary to ensure that they are connected one after the other. After connecting the voltage to the train's HV line, the HV converters of the individual wagons are activated and the voltage in the DC bus starts to rise. The inverter modules monitor DC Bus voltage, and when it reaches a sufficient level, the parallel configuration process is activated. The common bus connection control sequence is activated in the inverter. The delay value is generated and the timing starts. At the same time, the presence of voltage on the common network is checked. If no voltage is detected during the delay interval, this means that no other inverter is connected to the grid and therefore no synchronization is required and the output contactor can switch on, thus connecting the inverter output to the grid. If a voltage is detected in the common bus during the delay interval, this means that at least one inverter is already connected on the bus and therefore the process of synchronizing the inverter output voltage with the common bus voltage must be started. After the synchronization starts, the second random delay interval is activated. After this, the inverter voltage is synchronized with the grid and the output contactor can be switched on and the inverter output can be connected to the grid. After all inverters have been connected to the common bus, the individual loads can be also connected to the configured network. In one wagon there are 4 outputs for loads, which are connected to the common network by contactors. In order for the loads to be connected to the common bus even in the event of a drive failure, the switching of these contactors must be independent. This is achieved by feeding the contactor coils directly from the common bus. The time delay of the contactors closing is ensured by means of time relays. The loads will thus be connected to the bus after the time required to connect all inverters. The four contactors connecting the wagon loads are also switched one after the other with a time delay, which makes it possible to reduce the surge currents.

III. Inverters Power Sharing Control

In order to achieve the correct and stable parallel operation of the auxiliary converters AC outputs, suitable control software must be implemented in the inverters. The inverter control algorithm must ensure the correct load power sharing and the suppression of the circulating currents. There are several control techniques for parallel co-operation of inverters [1], which can be classified into two groups: Control strategies that require interconnection of inverter control circuits and control strategies without communication between the inverters. Control techniques from the first category have the advantage of accurate power sharing without a significant drop in voltage and frequency [2, 3]. On the other hand, the interconnection of inverters via a communication line increases the risk of failure of the entire parallel system in the event of a failure of this bus. Control strategies for parallel cooperation of inverters, which do not require their connection via a communication line, are usually based on the principle of droop control [4, 5]. Through this control method, real redundancy of the parallel system can be achieved.

The principle of droop control is based on the parallel operation of synchronous generators. The correct sharing of active and reactive power supplied to the common bus by individual inverters is achieved by appropriate control of the amplitude and frequency of the output voltage. The amount of reactive power is controlled by changing the amplitude of the inverter output voltage. The active power is controlled by the frequency of this voltage. As the active and reactive power increases, the voltage and frequency drop also increases, which is a disadvantage of this control strategy. Therefore, the control parameters must be set so that the voltage and frequency of the inverter do not fall below the permissible limit even at full load. Fig. 2 shows a block diagram of proposed control structure for parallel cooperation of inverters in synchronous reference frame. The derivation of this method is described in more detail in [6, 7].

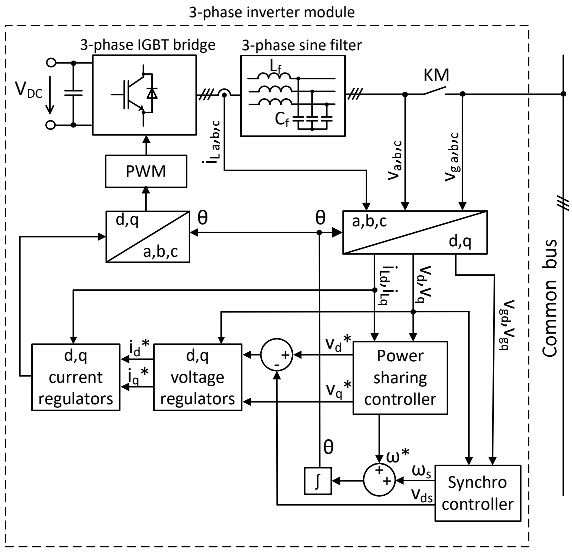

Fig. 2. Block diagram of the inverter control strategy for parallel operation.

Based on droop control principles with implemented virtual impedance, the suitable reference values of the angular frequency ω* and voltages v_d*, v_q* are calculated in the power sharing controller block according measured voltages and currents converted to d, q frame as follows:

$$\omega^* = \omega_0 - m \cdot P - m_d \frac{dP}{dt}, \tag{1}$$

$$v_d^* = V_0 - n \cdot Q - n_d \frac{dQ}{dt} - \left(-\omega L_v i_{oq}\right), \tag{2}$$

$$v_q^* = 0 - \omega L_v i_{od}, \tag{3}$$

where:
ω – inverter angular frequency,
ω_o – no load condition inverter angular frequency,
i_{od}, i_{oq} – output current d, q components,
P, Q – fundamental components of active and reactive power,
V_o – no load condition inverter output voltage amplitude,
L_v – virtual inductance,
m_d, n_d – derivative coefficients,
m, n – active and reactive power sharing droop coefficients.

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The voltages v_d*, v_q* calculated by power sharing controller are connected as reference values into the d, q reference frame control structure formed by the cascade topology of voltage and current regulators. The output of the current regulators are PWM reference values, on the basis of which switching signals are generated for the power transistors of the inverter three-phase bridge. The synchronization block adjusts the value of the reference voltage v_d* and the angular frequency ω* in order to synchronize the output voltage of the inverter with the common bus voltage. Based on the proposed strategy, the control software was created and implemented in the control system of the inverters.

IV. Experimental Results

Inverter modules with implemented software ensuring correct parallel cooperation and power sharing have been built into railway auxiliary converters. Subsequently, a system of four auxiliary converters connected by a common three-phase bus was set up for testing the properties of the proposed software, control parameter tuning, measurement and verification of power sharing in steady and dynamic states. The experimental setup is shown in fig. 4 and its simplified schematic diagram is in fig. 3. The converters are powered by a common HV transformer, which transforms the input single-phase voltage 400V AC to the secondary voltage 1500V 50Hz. The high-voltage modules convert this voltage to a 680V DC bus, from which the inverter modules with the implemented control software for parallel cooperation are supplied. The filtered inverter outputs are connected to a common three-phase bus via the output contactors. Two asynchronous motors with a power of 15 kW driving the fans were used as the load. Voltage and current waveforms are measured by an oscilloscope with current and voltage probes. The auxiliary converter main electric parameters are listed in table I.

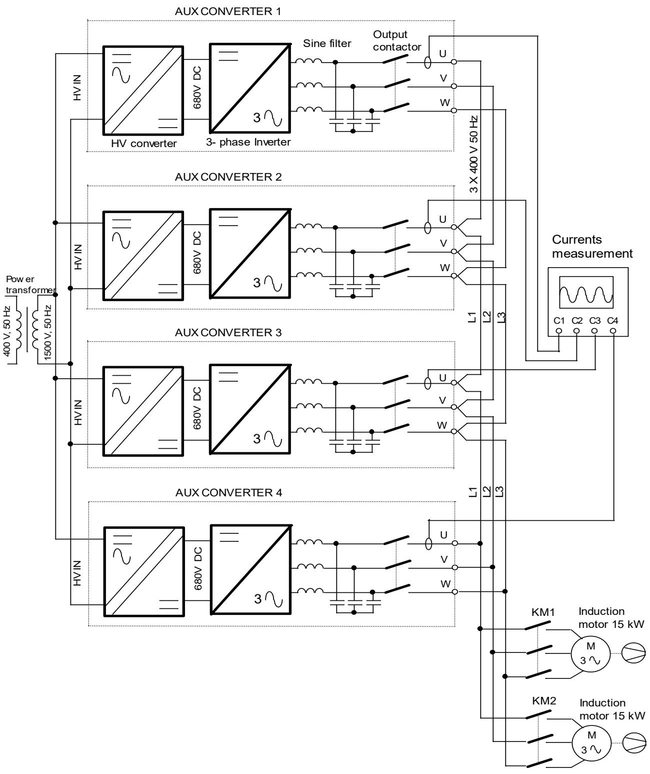

Fig. 3. Circuit diagram of the parallel connected railway auxiliary converters for experimental measurement.

TABLE I. Auxiliary Converter Main Parameters

Nominal input voltages	1000 V / 16,7 Hz, 22 Hz, 50 Hz 1500 V / 50 Hz 1500 V DC 3000 V DC
Nominal output power	55 kVA
Nominal output voltage	3x 400 V AC
Nominal output frequency	50 Hz
DC bus voltage	680 V DC
Switching frequency	8 kHz

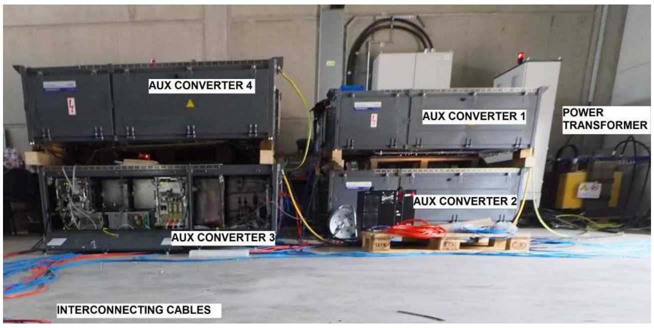

Fig. 4. Experimental setup of four paralel operated auxiliary converters.

First, the ability to synchronize and sequentially connect to a common bus of four inverters was verified. After switching on the 1500 V 50 Hz input voltage supplying the auxiliary converters, the input HV converters began to generate a DC bus voltage. After the rise of the DC bus voltage, the individual inverters were activated and sequentially synchronized and connected to the common bus according to the generated time delay. Fig. 5 shows the measured U-V line voltage waveform of the unloaded common bus.

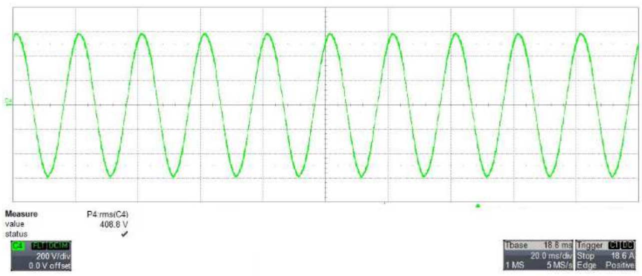

Fig. 5. Line voltage U-V measured on a common bus.

After verifying the ability of four inverters to work in parallel with the unloaded common bus, measurements were performed when connecting the load motors. The measured currents of the individual inverters and the total current to the motors after connection and during start-up are shown in fig. 6. Detail of currents during motor acceleration is shown in fig. 7. The currents of the first phase of the individual inverters were measured by means of current probes connected to a digital storage oscilloscope. The RMS values of the other phase currents are similar as a balanced three-phase load is used.

The inverter output currents are saturated to 85A rms. To achieve this current limitation, the output voltages of the inverters must be reduced to the corresponding value. This is ensured by the control structure in the d, q synchronous reference frame with the outer voltage and inner current loop. The measured RMS values of output phase currents of the individual inverters during load motors acceleration was:

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Converter 1 - 85.1 A, Converter 2 - 87.6 A, Converter 3 - 87.1 A, Converter 4 - 88.9 A. The RMS value of the total phase currents to the load motors was 347.4 A.

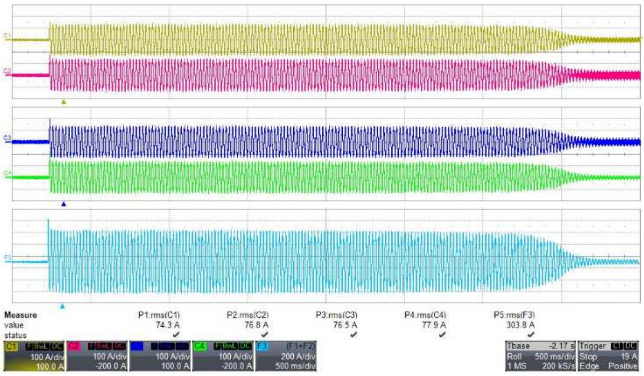

Fig. 6. Phase current of: converter 1 - C1 (yellow), converter 2 - C2 (red), converter 3 - C3 (dark blue), converter 4 - C4 (green), load motors - F3 (light blue).

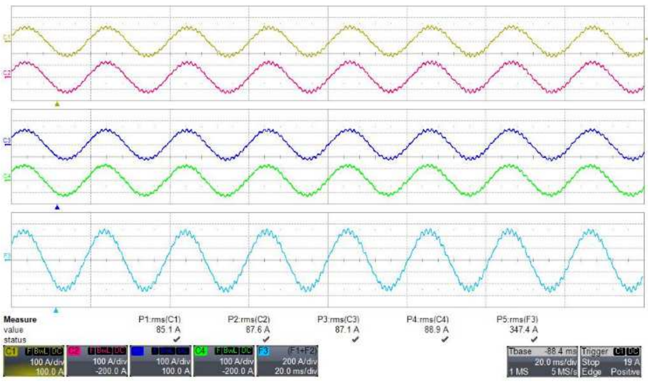

Fig. 7. Detail of currents during load motors accelerating.

Fig. 8 shows the measured currents in the steady state of the motors. It can be seen from the measured waveforms that the control structure implemented in the inverters ensures the correct sharing of the load currents by the individual inverters. The total load current 74.3A of the motors was shared by the individual converters as follows: Converter 1 – 17.5A, converter 2 – 18.4A, converter 3 – 18.9A, converter 4 – 19.5A.

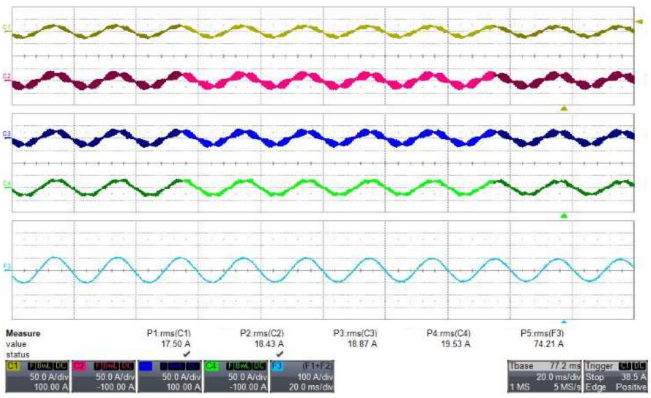

Fig. 8. Measured current waveforms of converters in steady state. C1 (yellow) – converter 1, C2 (red) – converter 2, C3 (dark blue)- converter 3, C4 (green) – converter 4, F3 (light blue)- load motors.

V. Conclusion

This paper describes the application of the proposed control strategy enabling the parallel cooperation of three-phase voltage source inverters. Inverter modules have been installed in railway auxiliary converters. The three-phase outputs of the inverters can therefore be interconnected via a common bus. The converters form a parallel system, which enables high reliability and availability due to redundancy. Greater system flexibility and configurability can also be achieved. In order to test the proposed control software for parallel cooperation of inverters, a system of four auxiliary converters was set up. Synchronization of converters, process of common bus forming and system stability during parallel operation were verified on this system. The parameters of the control structure were also tuned so that a satisfactory power sharing in steady and dynamic states was achieved. At steady state, the load current sharing was measured in the following ratio: converter 1 - 23.6%, converter 2 - 24.7%, converter 3 - 25.4%, converter 4 - 26.3%.

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