Measurement Of Parallel Operation Of Inverters To Common 3 Phase Network

Peter Jeck[1], Zdeno Biel[1]

[1]EVPU a.s., Trenčianska 19, 018 51 Nova Dubnica

Abstract In the article, we describe the measurement of parallel cooperation of inverters connected to a common three-phase network on train carriage with real loads. In the beginning, we will describe the used equipment and then we will describe the individual measurement procedures and their results. We will show the results of the measurements, when loading two inverters with two train carriage, four and eight carriage. Finally, the results of measurements with 6 inverters power on and a load of up to 14 train carriages.

Keywords measurement, inverter, 3 phase network, train carriage

JEL L62, L69

1. Introduction

Testing the parallel cooperation of converters on six wagons, which were continuously connected and thus created one common three-phase network, from which 14 compressors were powered. The aim of the testing was to test the latest software for inverters with vector control, intended primarily for the operation of several inverters in a common three-phase network. The converters were powered from high voltage and the power supply range 1.5kV AC 50Hz was used. Two types of refrigerated containers were used on the wagons: ThermoKing and Carier. The starting current of the ThermoKing compressors was higher (the instantaneous value was up to 200A, i.e. 100A higher than in the case of the Carier cooling unit). The reason for the more difficult start is the fact that the Thermoking does not have a bypass valve and during the start its compressors run into back pressure. Even the steady consumption of Thermoking cooling units (20-22A) was slightly higher than in the case of Carier (18-20A).

7 cars were connected to HV, but the three-phase outputs were not interconnected at first. We gradually connected them to the common network. During the test, the inverters were set to a nominal voltage of 3x380V. We have gradually verified the current operation with different number of converters (up to the number of max. 6 active converters) and different number of containers (up to the number of max. 14 containers).

2. Measurement of current for carriage load

First, we connected the first two inverters and tested parallel cooperation only with them using two refrigerated containers. Each container consumed approximately 20A when powered by 3x380V. In figure 1 below, it can be seen that the converters divided the consumption of 40A equally, about 20A each (the values of the phase currents in the picture also include the consumption of the internal sine filters). The output voltage under load dropped by 5V, i.e. to 375V.

2.1 A load of four containers

At the beginning, we let the load with two containers run for 5 minutes. The voltage was stable, and the currents did not fluctuate. After five minutes, we turned on the other two connected containers. The total consumption of 80A was divided between two inverters of approx. 40A each. The output voltage reached 3x370V at half the nominal load. Results of measurement is shown in figure 2.

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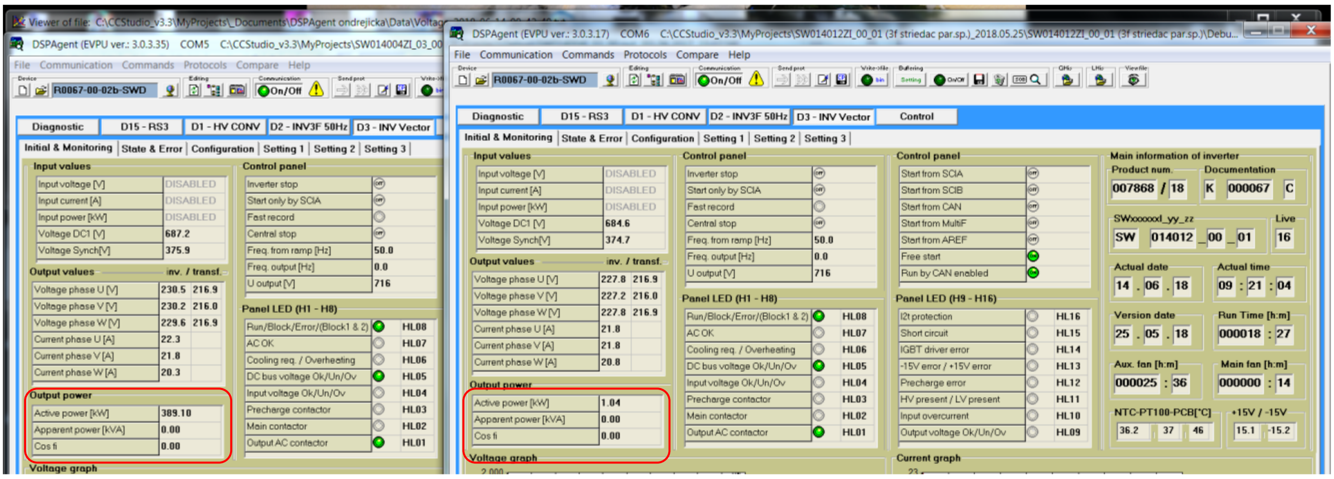

Current phase U [A]	22.3
Current phase V [A]	21.8
Current phase W [A]	20.3

Current phase U [A]	21.8
Current phase V [A]	21.8
Current phase W [A]	20.8

Figure1. Connection of two inverters and two refrigerated containers

Current phase U [A]	39.5
Current phase V [A]	39.9
Current phase W [A]	38.5

Figure 2. Connection of two inverters and four refrigerated containers

During five minutes, the voltage and current did not fluctuate, the power was distributed evenly the whole time. Then we turned off one of the two running inverters to see if the other inverter's output would oscillate, but there was no problem. All four containers were fed from one inverter and drew approximately the nominal load. The combined voltage at the output of the running inverter under this load dropped to 3x355V, which means a 25V drop from the nominal value (less than 7% drop).

Current phase U [A]	78.7
Current phase V [A]	75.5
Current phase W [A]	74.5

Figure 3. One inverter in operation with the connection of four containers

In figure 4 shows how the output voltage (red color) and output current (blue color) fluctuated during this transition event. After about 2.5 seconds, the output voltage was stabilized. The horizontal axis represents the time axis in seconds

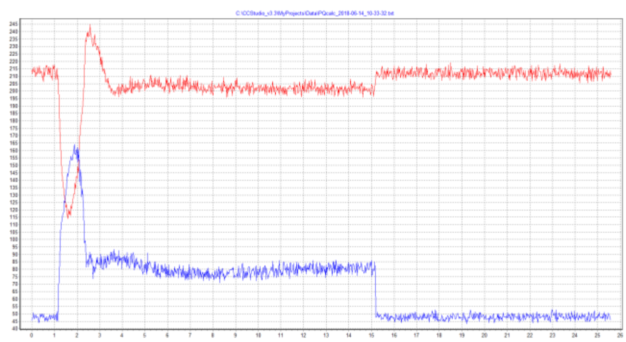

Figure 4. Output of the first inverter after switching off the second inverter when loaded with four containers

After restarting the switched-off inverter, the inverters again divided the power equally and both consumed 40A each. Not one of the cooling containers fell out during the transition. In this case, stabilization took less than 1.5 seconds, as we can see in figure 5.

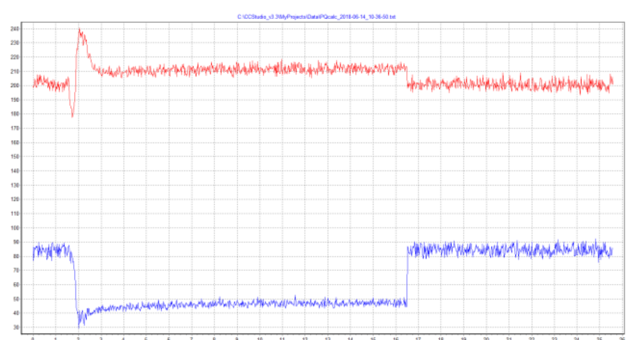

Figure 5. Output of the first inverter after the second inverter is switched on again when loaded with four containers

2.2 A load of eight containers

We left the first pair of converters blocked and put another pair into operation. All four wagons were connected to a common three-phase network so that we could use the full load (8 containers), which should represent the nominal load for two converters. Four containers were released and we released other containers gradually. First, we released the fifth container (Figure 6).

Current phase U [A]	52.4
Current phase V [A]	52.7
Current phase W [A]	51.0

Figure 6. Connection of two inverters and five refrigerated containers

After 20 seconds, we started two more compressors at the same time (Figure 7).

Current phase U [A]	70.3
Current phase V [A]	72.3
Current phase W [A]	69.1

Figure 7. Connection of two inverters and seven refrigerated containers

Both inverters worked the same, there were no voltage fluctuations even with a larger load that was added in steps, because in this case two compressors (sixth and seventh) were started at the same time. Each of the compressors had a capacity of up to 150A rms. After a minute, we released the last eighth container (Figure 8).

Current phase U [A]	78.7
Current phase V [A]	76.0
Current phase W [A]	77.7

Figure 8. Connection of two inverters and eight refrigerated containers

Even in this case, the combined voltage under this load dropped to 3x355V, which means it dropped by 25V (just like when only one inverter and four containers were started – see figure 3).

In this state, we let the two inverters run for an hour. The compressors cycled off and on during operation and none of them had a problem restarting. After an hour, we turned off the inverters and turned them on again with the compressors on, and the whole process started without any problems.

The compressors on one wagon are not connected to the common network at the same time. Each wagon has a Control Box in which there are time relays and it is guaranteed that two or four 3x400V outputs will never turn on at the same time (one wagon can fit two large or four small containers). During the test, pairs of large containers on each car were used throughout the train.

The moment when compressors are turned on also depends on their internal circuits (thermostats, control circuits). In the case of using eight refrigerated containers, it may happen that the compressors on several wagons are switched on at the same time. During the tests, it happened that two compressors turned on at the same time, but this did not mean any failure of the output voltage.

2.3 Successive switching on of 11 to 14 containers

We connected all 6 converters one by one and tested the start-ups of the compressors. The sharing of currents took place evenly, which we monitored on three inverters using the HWM5 diagnostic program. However, we managed to make screen copies of only two converters, because we got rain into one connection from the extension USB cables and it was no longer possible to monitor three converters at once.

We gradually released 10 containers. When starting the eleventh container, we monitored the behavior of the regulators on two inverters. According to figure 9 it can be seen that the voltage regulator (blue color) and the current regulator (red color) behave identically and at the same time request the same output current (in the blue circle) and output voltage (in the red circle). The output current in this case should be, according to the calculation for 11 containers and 6 inverters (11 containers x 20A) / 6 inverters) about 36.6A. In figure 10, the current output current of the first one of the inverters can be seen in the green circle.

In the case of connecting twelve containers, the output current in this case should be, according to the calculation for 12 containers and 6 inverters (12 containers x 20A) / 6 inverters) about 40A. According to figure 9, it can be seen that the inverters distribute the loads equally. It is the same inverter load as in figure 2, where there were two inverters and four containers.

Current phase U [A]	40.9
Current phase V [A]	41.7
Current phase W [A]	40.9

Figure 9. Connection of six inverters and 12 refrigerated containers

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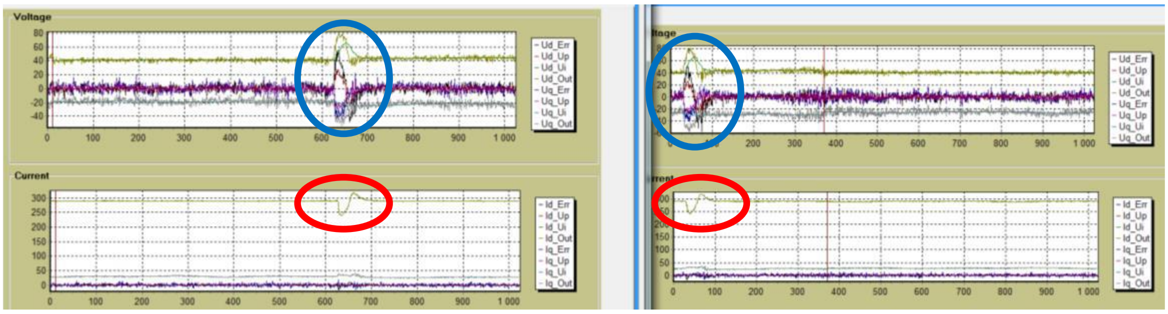

Figure 10. Behavior of SW controllers when connecting six inverters and 11 refrigeration containers

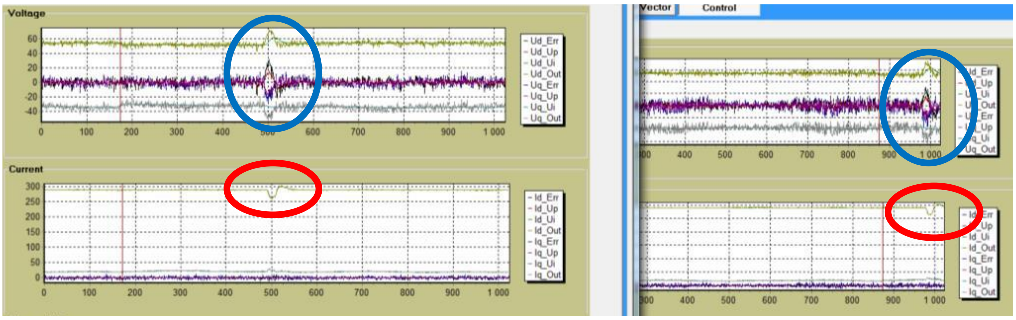

Figure 11. Behavior of the regulators when connecting six inverters and 13 refrigeration containers

Even in the case of releasing the thirteenth container, it can be seen according to figure 11, that the regulators of two of the six converters behave identically and the currents are divided equally between the 6 converters (figure 12).

Current phase U [A]	45.8
Current phase V [A]	46.8
Current phase W [A]	45.3

Figure 12. Connection of six inverters and 13 refrigerated containers

In the next picture you can see the connection of up to 14 containers, and the wagon set loaded in this way was allowed to run for more than 1 hour, and then we turned off and on the HV and all the converters started and everything started without problems (see figure 13).

Current phase U [A]	50.2
Current phase V [A]	49.3
Current phase W [A]	48.5

Figure 13. Connection of six inverters and 14 refrigerated containers

Figure 14 shows the graphical onset of the entire load. In the tenth second, all inverters (6 units) are started, and from the 40th second, all the cooling containers gradually start running. The last 14 started in the 260th second and the converters remained stable throughout the run. At some times, several containers were connected automatically at the same time, which is reflected in a higher capture current, for example at times 41s and 50s.

In the event that several compressors are already running, the inrush current from the inverter when the next compressor is turned on is not so great, because the other running motors transfer their energy to it.

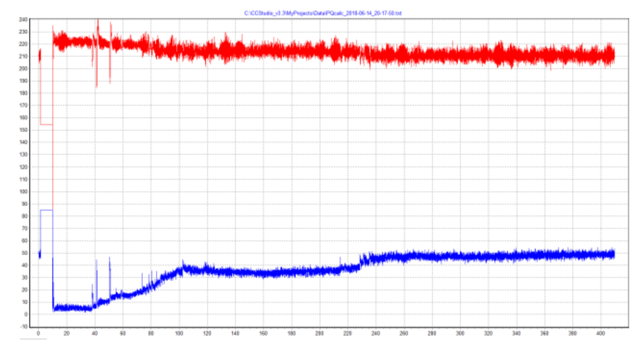

Figure 14. Graphical interpretation of the progressive load of the converter

3. Conclusions

Parallel cooperation was verified on six converters. These converters created a common continuous three-phase network 3x380V. At nominal load, according to the data from the diagnostic program, this voltage dropped to 3x355V (about 7%). We chose a setting where the desired voltage in the system was set to 380V, in order to verify the operation of the inverters even at the lower limit of the output voltage, where compressors usually draw a higher current. Due to lack of time, we could not check the operation of the converters at the nominal voltage of 3x400V.

By measuring, we verified that the division of power between the individual converters is uniform with minimal deviations. With various step changes in the load, the continuous network was stable, did not oscillate and supplied sufficient voltage to power the refrigerated containers.

By short-term switching off of HV, passage of the set through a voltage-free section was simulated. After re-discovering the HV, a continuous network was established without complication and all 14 containers connected to six inverters were up and running within 4 minutes. The time when the compressors were turned on was individual depending on the thermostats and control circuits of the compressor in the container.

The inverters were put into operation by the superior system only after the HV converter announced the completed pre-charge and confirmed the operation. In this way, the converter did not oscillate during the inverter shots, and a common three-phase network could be created within five seconds of receiving permission to operate the inverters.

Also, during the measurement, we switched off and on the individual converters, either when empty or with a loaded continuous network. We had 6 converters and 14 containers at our disposal. So we blocked one, two and three converters. The continuous network was still active and was able to power 14 compressors. In these tests, we turned off and on random containers, and verified whether the three inverters could create a solid and, above all, stable continuous network. The inverters had no problem with these load step changes and the system was stable throughout the operation of the inverters, regardless of whether there were 3, 4, 5 or 6 inverters working into the common three-phase network.

The operation of the inverters into a common three-phase network with different numbers of active inverters and different numbers of containers was documented using a copy of the screens of the HWM5 diagnostic program.

Unfortunately, we were unable to make oscilloscope recordings, as the weather was rainy throughout the measurement period and the 230V power supply for powering the oscilloscope was not provided either.

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REFERENCES

[1] J. Skorvaga and M. Pavelek, "Comparison of 3D models of the circular and square coupling coils for WPT with power 44kW," 2022 ELEKTRO (ELEKTRO), 2022, pp. 1-6, doi: 10.1109/ELEKTRO53996.2022.9803799.

[2] [2] J. Skorvaga and M. Pavelek, "Review on high power WPT coil system design," 2021 International Conference on Electrical Drives & Power Electronics (EDPE), 2021, pp. 13-18, doi: 10.1109/EDPE53134.2021.9604108.

[3] [3] Kindl, V.; Frivaldsky, M.; Zavrel, M.; Pavelek, M. Generalized Design Approach on Industrial Wireless Chargers. Energies 2020, 13, 2697. https://doi.org/10.3390/en13112697

[4] [4] A. Perić, H. Pauković, M. Miletić and V. Šunde, "Development of voltage source converter using HiL simulation system," 2019 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), 2019, pp. 168-173, doi: 10.23919/MIPRO.2019.8757020.

[5] [5] M. Kazmierkowski and L. Malesani, “Current control techniques for three-phase voltage-source PWM converters: A survey,” IEEE Trans. Ind. Electron., vol. 45, no. 5, pp. 691–703, Oct. 1998.

[6] [6] I. J. Gabe, F. F., K. Palha and H. Pinheiro, "Grid connected voltage source inverter control during voltage dips," 2009 35th Annual Conference of IEEE Industrial Electronics, Porto, 2009, pp. 4571-4576, doi: 10.1109/IECON.2009.5414865.

[7] [7] M. Schweizer and J. W. Kolar, “Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications,” in IEEE Transactions on Power Electronics, vol. 28, no. 2, pp. 899-907, Feb. 2013.

[8] K. A. El Wahid Hamza, H. Linda and L. Cherif, "LCL filter design with passive damping for photovoltaic grid connected systems," IREC2015 The Sixth International Renewable Energy Congress, 2015, pp. 1-4, doi: 10.1109/IREC.2015.7110945.