TRANSFORMER INRUSH CURRENTS IN A NPC BASED CONVERTER SYSTEM FOR COLD IRONING APPLICATIONS

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Keywords

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Abstract

In this paper, the effects of the transformer inrush currents in a real plant for *Cold Ironing*, with a power equal to 11 MVA, based on a conversion system using 4 NPC converters in parallel is presented. The first part describes the plant and the related problems, while in the second part two possible solutions are presented with the support of real measured data.

Introduction

In the lasts years, the concerns about environmental issues in the main cities of the world have significantly increased and a major pollution problem occurs in the cities with big harbors, where, when the vessels arrive, they normally continue to be energized by their internal generators, optimized to obtain a low cost energy, thanks to the very inexpensive fuel used, i.e., Heavy Furnace Oil (HFO). However, such a fuel, which significantly pollutes the air, causes no problems in an offshore navigation, but becomes intolerable when used inside the harbor in a big city [1]. The term *Cold Ironing* means that the generators are turned off when the vessel is energized from the harbor mains and so their iron becomes literally cold [2].
This paper refers to the recent first implementation of a *Cold Ironing* system in one of the main harbors in the Mediterranean Sea, at Genova, in Italy.

The actual converter

The converter implemented is shown in Fig. 1-3. The input stage corresponds to a 24 pulse diode rectifier, feeding a single DC link. The output stage corresponds to 4 NPC converters [3] in parallel, feeding each one a single primary of the output transformer OT. The rated voltage of the DC-link is ±2700V and the output voltage of the output transformer is selectable among 11kV, 10kV and 6kV, providing an output rated power of 11MVA, 10MVA and 6MVA, respectively. The 4 NPC converters are synchronized with an optical daisy chain, allowing the implementation of an interleaved system.

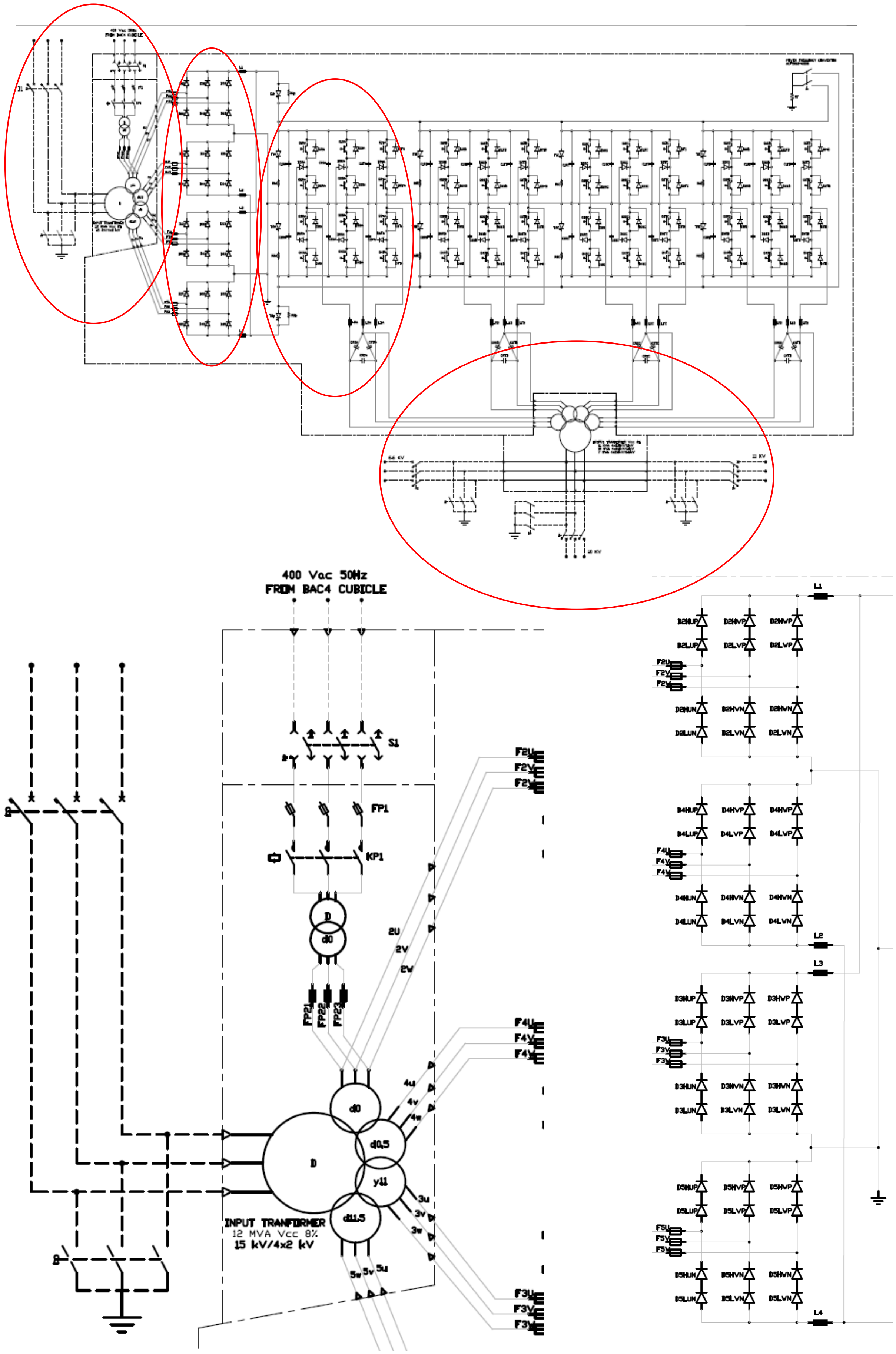

Fig. 1. Cold Ironing converter system, top: general overview, bottom left: input transformer, right: 24 pulse rectifier stage

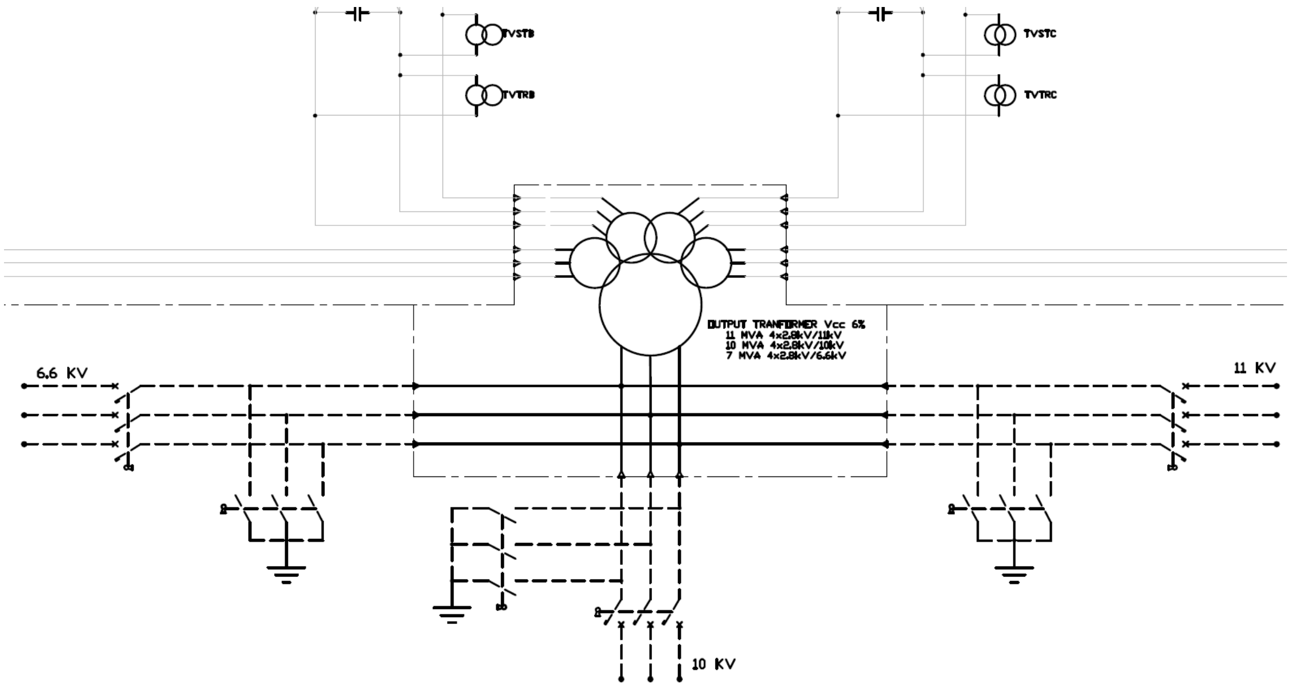

Fig. 2. Cold Ironing Converter System, output transformer

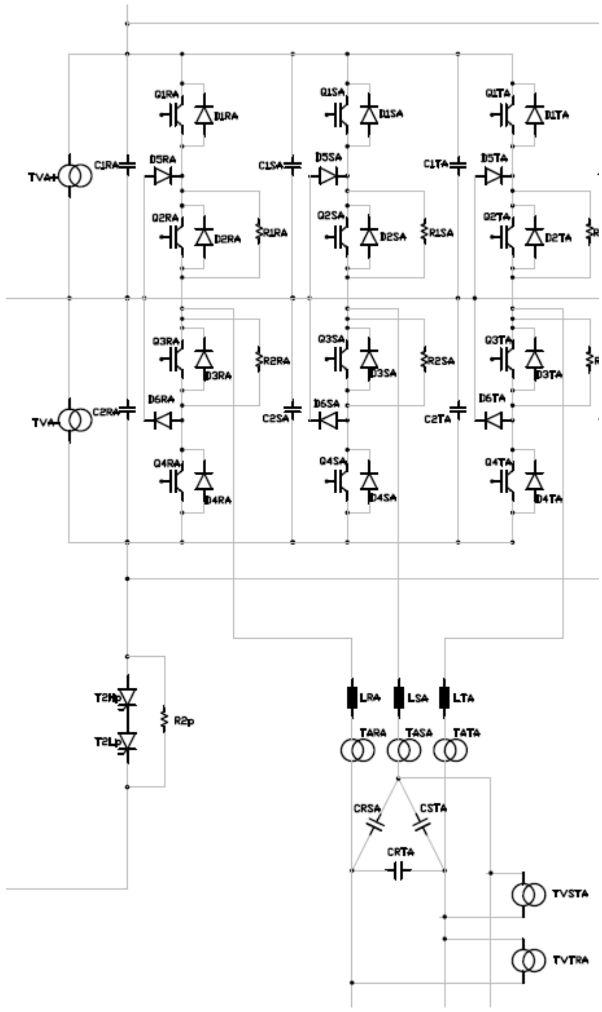

Fig. 3. Cold Ironing converter system: single NPC stage

The system is designed to feed a single MV (Medium Voltage) vessel at 50 Hz or 60 Hz, or different and simultaneously LV (Low Voltage) vessels at 50 Hz or 60 Hz. The converter 3D scheme is shown in Fig. 4, whereas the image of a NPC converter, a NPC filter and the rectifier stage are shown in Fig. 5. Fig. 6 shows a single phase of a NPC converter, Fig. 7 shows the output phase voltage upstream the filter, while Fig. 8 shows the output voltage of a NPC stage downstream the filter, the output current and the DC link voltage in a 60Hz configuration.

Before the system is turned on, the input transformer is pre-magnetized by a dedicated circuit that is shown in Fig. 1. The output transformer OT is magnetized directly by the converter, through a V/f ramp.
The converter has a weight of 14400 kg and an efficiency of 98%. The cooling system consists of water-to-water exchanger and closed loop of deionised water-cooling by means of deionised water in forced circulation, using two redundant pumps. Pressure drop of cooling circuit is maximum 0.5 bar at 530 l/min.

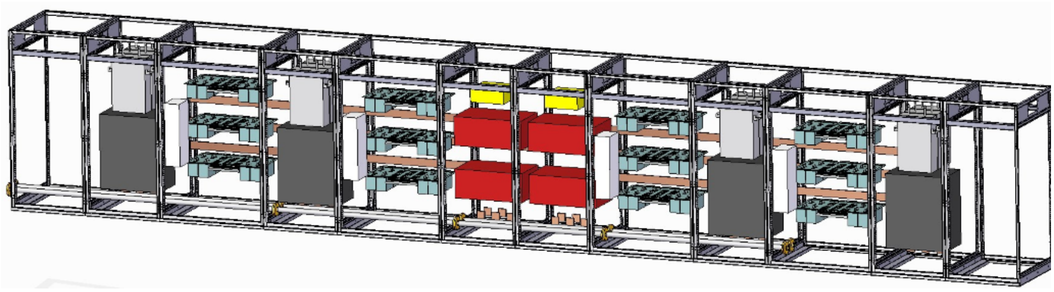

Fig. 4. Converter system scheme

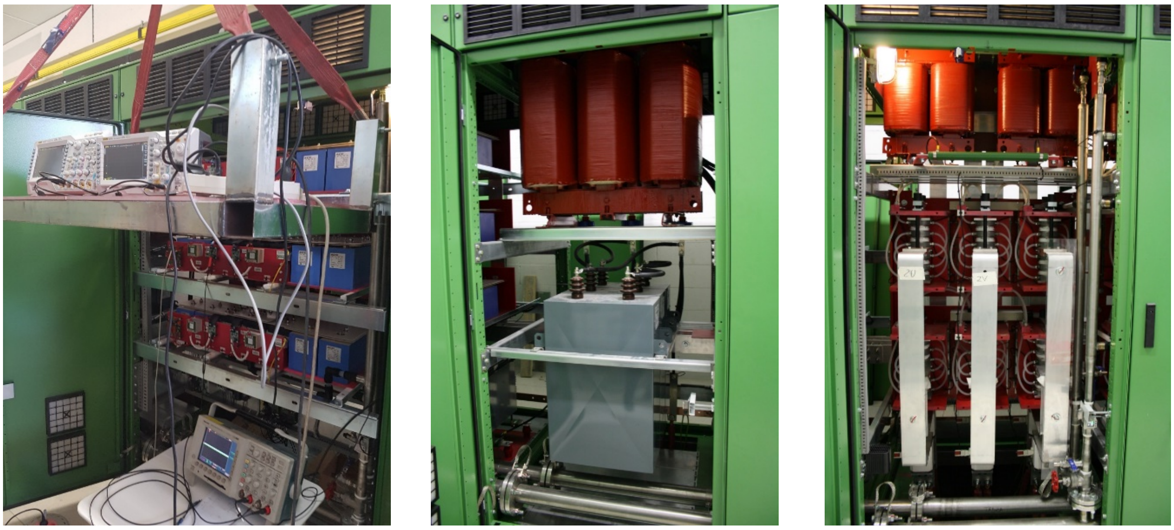

Fig. 5. Converter system: left, single NPC converter; center, NPC output filter; right, 24 pulses rectifier stage

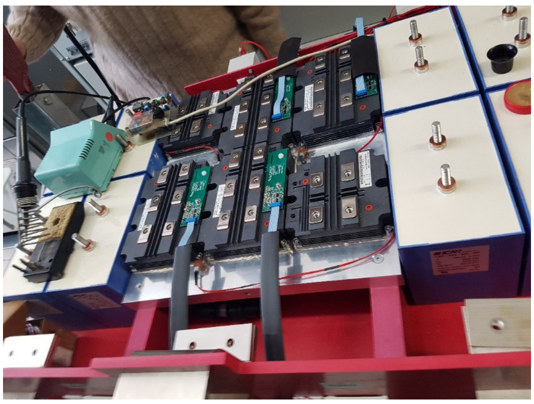

Fig. 6. A single phase of a NPC stage

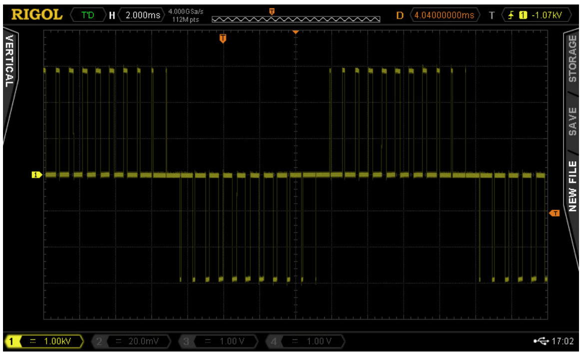

Fig. 7. NPC output phase voltage at 60Hz operation mode

Fig. 8. NPC output waveforms: left, voltage converter at 50 Hz, downstream the output filter; right, in blue the measured current, in yellow the DC link voltage and in cyan and magenta the output voltages downstream the output filter

When working in LV mode, each vessel is fed by a dedicated transformer, connected directly to the output transformer OT shown in Fig. 3.
The first LV vessel connected to the system is connected through a transformer T1 powered on together with the converter in the same V/f ramp. All the others transformers remain unconnected.
When a second LV vessel arrives, a second transformer T2 needs to be connected to the system, without interrupting the power of the first vessel, but at this time, of course, it is no more possible to power the second transformer T2 for the second vessel with a V/f ramp, as the first vessel is already powered with T1.
In this case, the second transformer T2 is connected directly in parallel with T1, generating inrush currents that are too high and generate a trip condition in the converter that turns off the converter itself and consequently, interrupts the power supply to all the vessels connected to it. This kind of trip is clearly unacceptable because it’s cause of a general blackout in all the vessels powered by the harbor Cold Ironing system, in this specific application, up to 10 vessels.
In Fig. 9 it’s possible to appreciate the section of the electrical network supplying two quays of the harbor and in Fig. 10 one of those quays supplying a LV vessel absorbing about 800 kVA.

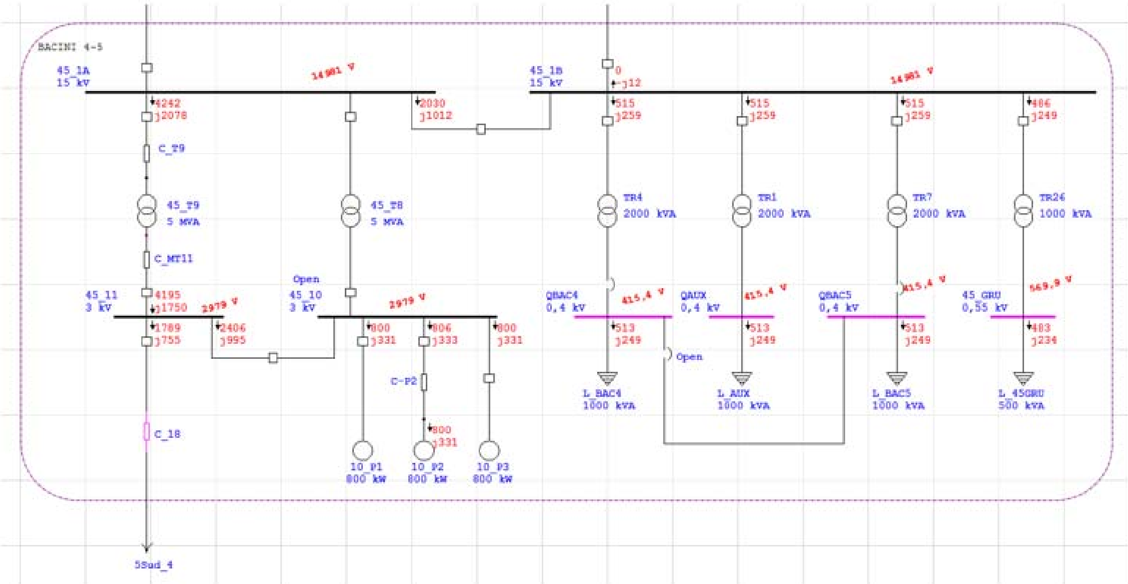

Fig. 9. Electrical network for quays number 4 and 5 supplied by the converter.

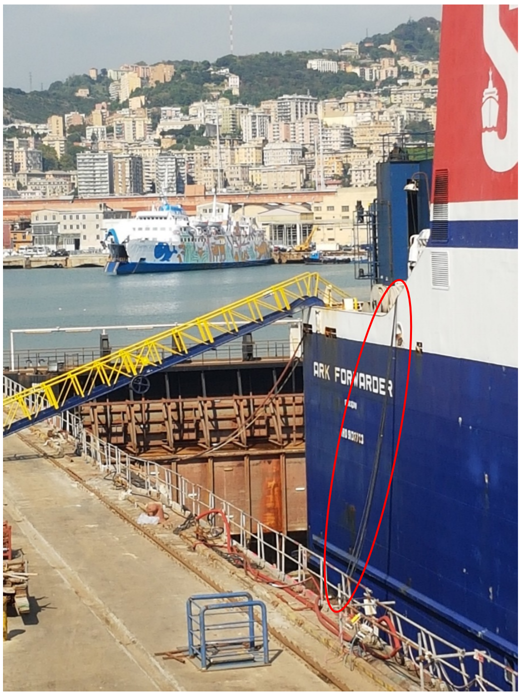

Fig. 10. Quay number 5 supplying a LV vessel, marked in red the cable connecting the vessel.

Inrush transformer insertion analysis

Recently, several authors have studied the inrush current phenomena [4-5] proposing different solutions. The easiest one was adopted by the authors and consists of asking the converter to be allowed to connect a second vessel to it. In such a moment, the converter output voltage is reduced by a factor of 0.5. Once the output voltage is half the rated value, the second transformer T2 is connected in parallel, but due to the decreased voltage, there are not high inrush currents and no trip happens. Once T2 is connected, the converter immediately increments its output voltage to the rated one in about 100 ms, with a voltage ramp.
The transient condition during the connection of the second vessel seems to be acceptable in general for the first vessel and in this moment this is the solution adopted for this situation.
The transformers can operate at 50 Hz and 60 Hz; the more stressful situation corresponds to the 50 Hz, case that needs a decrement of 50% of the output voltage in order to guarantee no inrush currents problems, whereas at 60 Hz operation, it's enough to decrement the output voltage by a factor of 40%.
Fig. 11 shows the measured output currents of a NPC converter stage (in yellow the current of a phase including the output filter current), during the connection of T2, with the output voltage decreased by a factor

of only 20% at 60Hz. The measure starts 50 ms before the insertion of T2. After the insertion, it's possible to appreciate the transient of the inserted transformer, with the typical DC current component. It's possible to appreciate how, after more than 300 ms, the current increases in an uncontrolled way, producing a current trip and consequently a blackout condition. It's worth to note how the insertion current of T2 is not too high, and then it does not represent the real problem, but the real problem seems to be the transient current generated by T2 that causes the saturation of OT, after the insertion of T2 and not during its insertion.
The actual strategy of inserting the transformers decreasing the converter output voltage works without problems, but clearly the optimal solution should be to control the DC current component of OT with T1 already inserted when the transformer T2 is inserted. Unfortunately, the system is now in use with several connected vessels and it has not been possible to test the proposed method, but it was implemented in the mock-up system, a scaled-down system described in the following section.

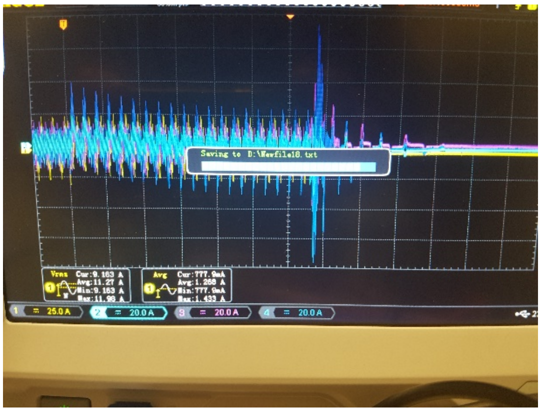

Fig. 11. NPC converter output currents at 60 Hz operation, downstream the output filter. Time base 50ms/division, current 200A/division. In blue the NPC output current, in yellow, cyan and magenta the NPC output currents downstream the filter.

The mock-up converter

Before the construction of the 11MVA converter, a mock-up converter was developed as shown in Fig. 12. The scale factor used was 10 for voltage and 50 for current and consequently the power reduction factor was 500. The mock-up converter was developed in order to test the firmware of the final converter.
The control of the transformer DC current component was developed and tested on the mock-up converter, waiting for the availability of the 11MVA converter for the final test.

Output DC current component control

LEM sensors measure the currents at the output of each NPC phase, upstream the output filter. The control strategy adopted consists of simply calculating the moving average of the measured current over a time window of a single electrical cycle, i.e, 20 ms for 50 Hz and 16 ms for 60 Hz. With no DC component the moving average should be always zero.
The PWM switching frequency is 1320 Hz for 60 Hz operation mode and 1100 Hz for 50 Hz operation mode, i.e., in each electrical cycle there are 11 positive pulses and 11 negative pulses in the output phase voltage of each NPC stage, as shown in Fig. 7. The acquisition rate for the currents is twice the switching frequency and the moving average is also updated at twice the switching frequency.

The DC current component control adopted is implemented by imposing the DC current component to two phases only, as the sum of the DC components of the three phases is always zero. The DC component signal error is the output of the moving average filter and is controlled with a proportional control; its output is added to the sinusoidal modulating signal at the PWM modulator input, as shown in Fig. 13. This proportional control is limited to ± 5% of the modulating index in order not to disturb excessively the vessel loads already connected to the converter. This control is applied only to the first NPC converter that acts as a master, giving the modulation index and phase to the others 3 converters that don't add a corrective signal to the modulating signals.

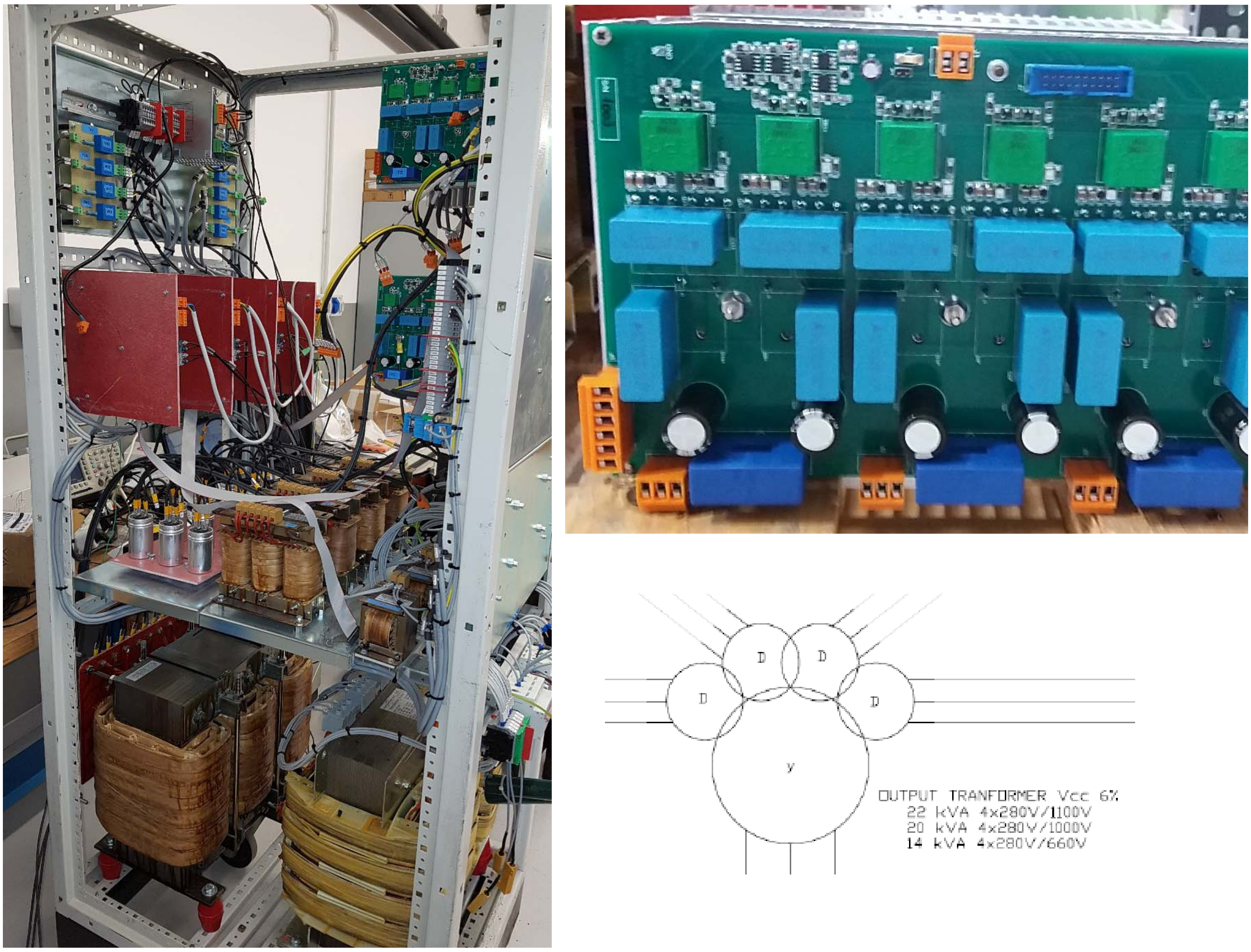

Fig. 12. Mock-up: left, whole system; right top, NPC card and, right bottom, output transformer.

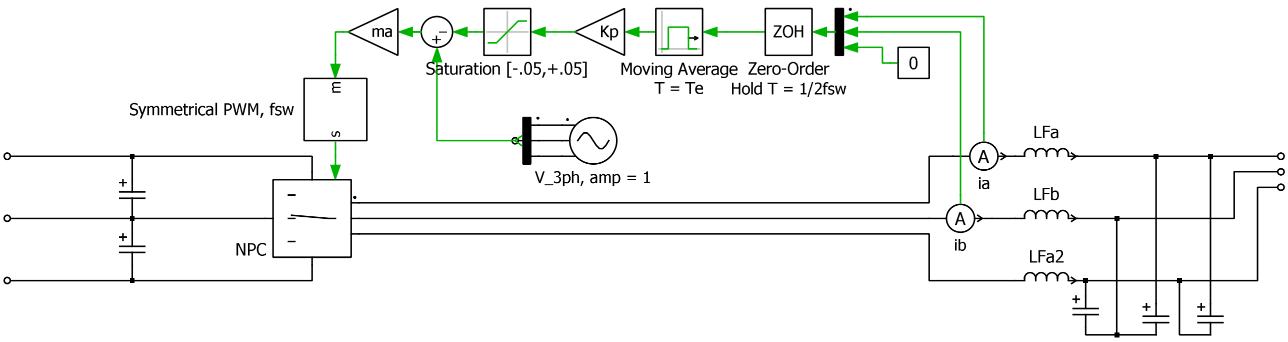

Fig. 13. DC current component control

This control was tested with the mock-up without any load and connecting a second transformer of 5kVA at the 1000V output of the output transformer, as shown in Fig. 14. This setup is worse than the case of the full-scale converter, because there is no transformer connected to the output transformer during the insertion, so there is no sympathetic inrush current [6] contribution, but the phenomena is more evident. The inrush current was not used in the control, but was measured, with a Rogowsky probe, for a better understanding of the system behaviour. Fig. 15 shows some currents with the DC current component control enabled during the transformer insertion. The insertion current in green reaches a peak of 4 A. The NPC output currents are shown in blue and yellow. The correcting signal, output of the DC component is shown in red.

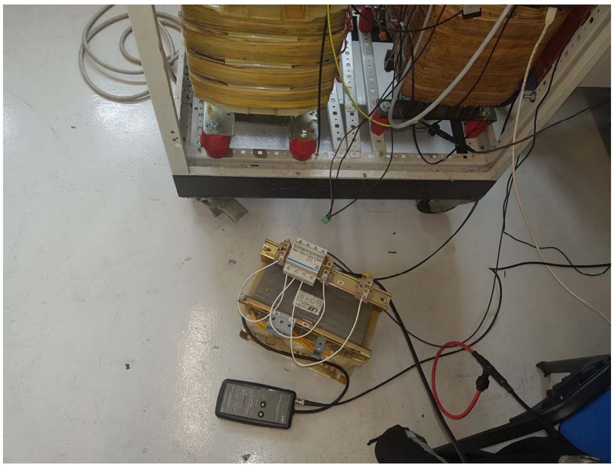

Fig. 14. Transformer connected downstream the output transformer for studying the inrush current problems

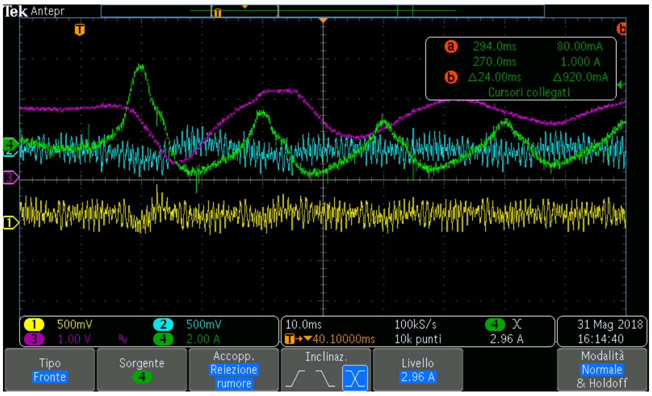

Fig. 15. DC current component control enabled: NPC output current, phase a blue, phase b yellow; inrush current green, DC component compensating signal red

The same situation is shown in Fig. 16, where the DC component control is disabled, i.e., the correcting signal is not added to the modulating signals. In this case, it can be appreciated how, owing to a 2 A inrush current, the system turns off due to an overcurrent fault, showing how the control is actually effective.

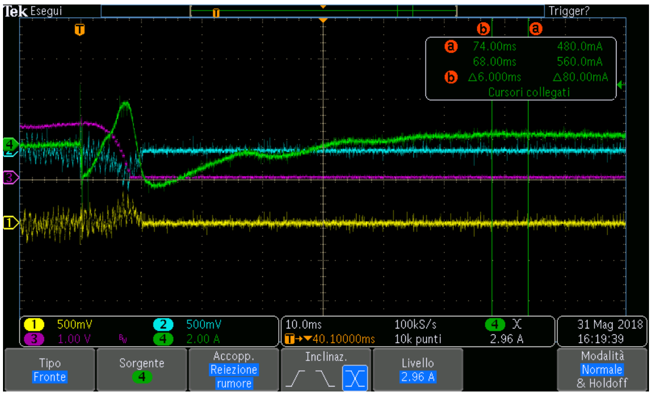

Fig. 16. DC current component control disabled: NPC output current, phase a blue, phase b yellow; inrush current green, DC component compensating signal red

Conclusions

A real Cold Ironing conversion system, with a power equal to 11 MVA was developed by the authors. This system powers a real and complex electrical network having the capacity for connecting up to 10 vessels simultaneously fed by the converter.

The serious problem caused by the inrush current related to the insertion of high power transformers in the network was analysed and a control of the DC component current was developed and verified in the mock-up converter. The developed control gives good results and as soon as possible it will be tested in the full-scale converter. The results obtained with the mock-up system allows one to expect better results in the full-scale system, due to the slower increase of the transient currents.

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