Analysis and Construction of Static Inverter with Multi-windings Transformer for High Power Voltage Source

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Abstract— High power static voltage inverters found their application in a power conversion for isolated power grids, especially in the shipbuilding and the maritime industry. Most of the problems related to the design of such inverters are that very often nominal power of such devices is comparable to nominal power of its load. In this contribution a design of such voltage source, its computer simulations and experimental results are shown.

1. INTRODUCTION

Ships and shipping industry is a big part of global economy. Without shipping international trade, import/export of raw materials or goods would be not possible. Global trade has permitted a variety of resources to be widely accessible.

At December 2010 world fleet of propelled sea-going merchant ships of no less than 100 GT includes 104 304 ships with an average age of 22 years and cargo carrying fleet in 2011 is 55 138 ships of an average age 19 years [1].

For shipyards or ports located in the city area it is important to reduce the impact of the activity of such facilities on the local community. To reduce pollution and noise generated by an on board generators or in case of technical reasons (vessel is under a maintenance is shipyard, and it cannot use its own on board power generator) shipyards or ports owners can install an on-shore power supply [2].

Additionally this solution gives economical savings — power from the local electrical net-work is cheaper than generated by diesel generators, particularly when the oil prices continuously growth.

The problem arises, when the ship's electrical network standard is different from the local electrical grid — it cannot only be used transformers to change voltage level, but it also it is needed to change the frequency.

To do this a converter is necessary, which transforms electrical energy from local network to the required by the ship network. One type of converters is the power inverter, which is a power electronics device that converts energy from local grid to the ship's electrical network.

2. REQUIREMENTS FOR THE VESSEL'S ELECTRICAL POWER SUPPLY

A voltage source which is used to supply ship's internal electrical network need to meet specific characteristic imposed by the country of registration of the vessel laws. This regulations describes minimal requirements for the electrical generators, if it should be used as a power supply for ship's electrical network. This requirements also relates to an auxiliary power supply such us the on-shore power supply.

Vessels, according to its type, registered in Poland has to follow rules presented in the *Rules for the Classification and Construction of Sea-going Ships, Rules for the Classification and Construction of Small Sea-going Ships, Rules for the Classification and Construction of High Speed Craft* or *Rules for the Classification and Construction of Inland Waterways Vessels* of the *Polski Rejestr Statków.*

Requirements for main source of electric power for Sea-going Ships are presented in Part *VIII. Electrical Installations and Control Systems.* Table 1 shows main requirements for ship's electrical power supply [3].

As it is stated above there are two main problems associated with the design of electrical power supply — maintain voltage in specific range with low voltage deviation (low harmonics distortion) and withstand overload and short-circuit currents. This has to be kept in mind while designing such devices.

3. HIGH POWER VOLTAGE SOURCE SYSTEM

The voltage source proposed in this paper consist of two main parts: a Voltage Source Inverter (VSI) controlled by a microcontroller and a multi-winding transformer. A block diagram of this device is shown in Figure 1.

Table 1: Main requirements for ship's electrical power supply (A.C. system).

No.	Type of Requirement	Overview of Requirement
1	Overcurrent	A.C. system — 50% for 120 s
		Withstand three-fold rated current for 2 s
2	Short Circuit	Peak value of short-circuit current less then
		fifteen-fold rated current
3	Voltage Changes	Voltage in maintained within ±3.5% at rated load
4	Voltage in Load Changes	85%–120% of the nominal voltage for maximum 1.5 s
5	Voltage Deviation	Less than 5% — voltage instantaneous value to the first harmonic:

The multi-winding transformer is a three phase transformer with the one winding with N turns of coil per phase on the primary side and the two windings with N_1 and N_2 turns of coil per phase on the secondary side. The schematic of the transformer is shown in Figure 2.

The main elements of the Voltage Source Inverter (VSI) are switching devices. For small to medium power systems (up to 100 kVA) it is possible to use IGBT modules. With high working frequency (about 10 kHz) and output filters it is easy to generate sufficient output voltage with very low distortions [4].

The problem arises for high power systems (over 1 000 kVA). In that case none transistors can be used. Instead thyristors are used. Working frequency is lower — about 1 kHz and less for higher powers.

The Voltage Source Inverter (VSI) presented in this paper is a three phase inverter with thyristors as a switching device [5]. The output phase voltage is a square wave, with working frequency 50 Hz and conducting angle between 120 to 180 degrees. Figure 3 shows an example of VSI output phase voltage.

With low working frequency of the VSI the transformer parameters like number of turns of the coil in secondary windings and connections of those windings was optimized to minimize the Voltage Deviation and the Total Harmonic Distortion (THD) in output voltage. The Voltage Deviation mentioned in the part 2 of this contribution is measured according to this equation:

$$u_w = \frac{\Delta U_m}{\sqrt{2}U_1} \cdot 100\% \tag{1}$$

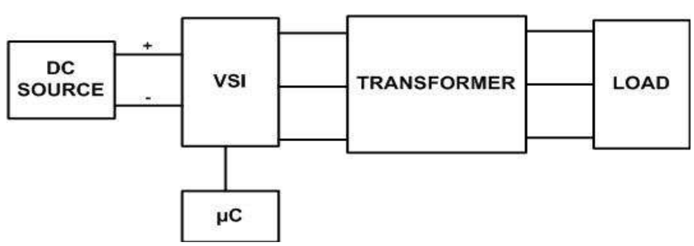

Figure 1: Block diagram of the proposed high power voltage source.

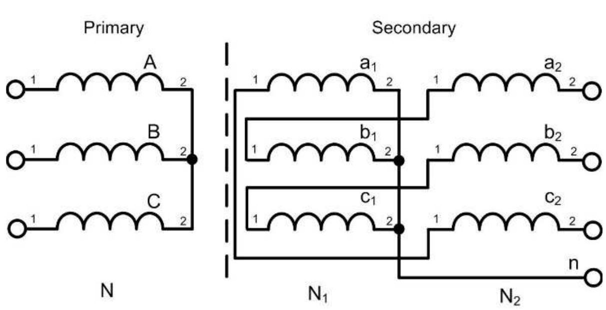

Figure 2: Schematic of the multi-winding transformer.

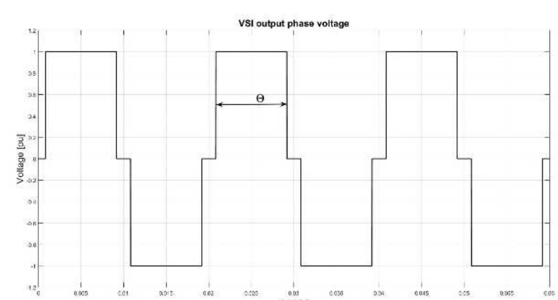

Figure 3: The VSI output phase voltage. Frequency $f = 50\,\text{Hz}$, conducting angle $\Theta = 150°$.

where:
ΔU_m — the maximum value of the distorted voltage,
U_1 — the first harmonic effective value of voltage,
and THD according to this equation:

$$K = \frac{1}{U_N}\sqrt{\sum_{v=2}^{n} U_v^2} \cdot 100\% \tag{2}$$

where:
U_N — effective value of the network voltage (RMS),
U_v — effective value of voltage of v-number harmonic,
n — number of higher harmonic.

4. COMPUTER SIMULATIONS

The proposed High Power Voltage Source with multiple configurations of the transformer was simulated in MATLAB. Additionally it was optimized for the minimal THD and minimal Voltage Distortion in the output voltage in MATLAB. All simulations was made with this parameters:

- High Power Voltage Source VSI — 3-phase, output frequency 50 Hz, square wave, output phase voltage 230 V (RMS), variable conducting angle,
- High Power Voltage Source Transformer — 3-phase, power $S_N = 1\ 000\,\text{kVA}$, input/output phase voltage 230 V/230 V (RMS), $U_K = 6\%$, $I_{0\%} = 1.3\%$, $P_0 = 2\ 000\,\text{W}$, $P_N = 10\ 500\,\text{W}$, variable N_1 and N_2,
- Load — 3-phase, resistive, 750 kW.

Figure 4 shows output voltage waveforms for different transformer configuration (primary winding connected in a wye and delta) with a first harmonic compound and calculated parameters (THD, Voltage Deviation, etc.).

5. EXPERIMENTAL RESULTS

The experimental system was build and tested according to simulation results. It consisted of a DC voltage source, a VSI controlled by microcontroller (ARM7) and an output multi-winding

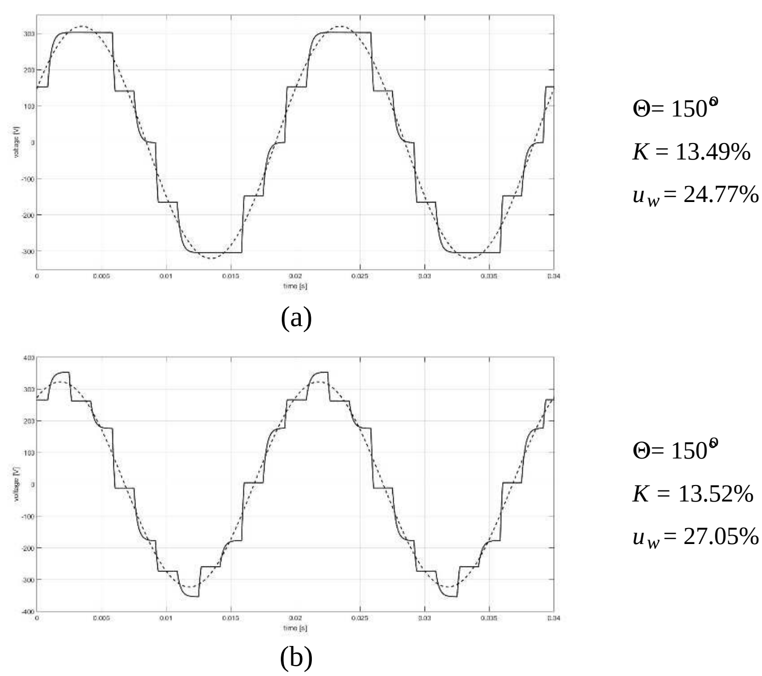

Figure 4: The output voltage waveform (solid) and first harmonic (dashed) for different configurations of the transformer: (a) primary winding connected in wye, (b) primary winding connected in delta.

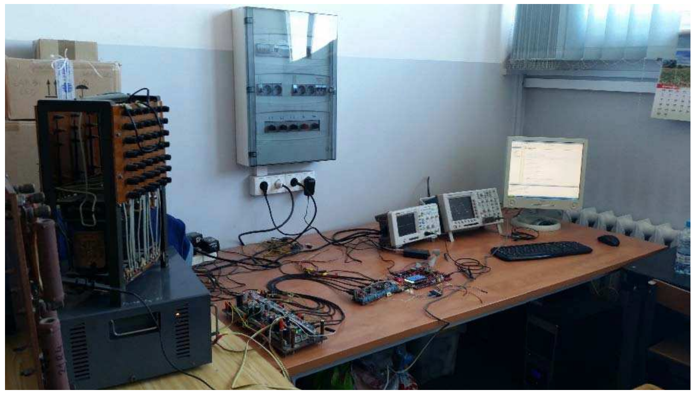

Figure 5: The photo of the experimental setup.

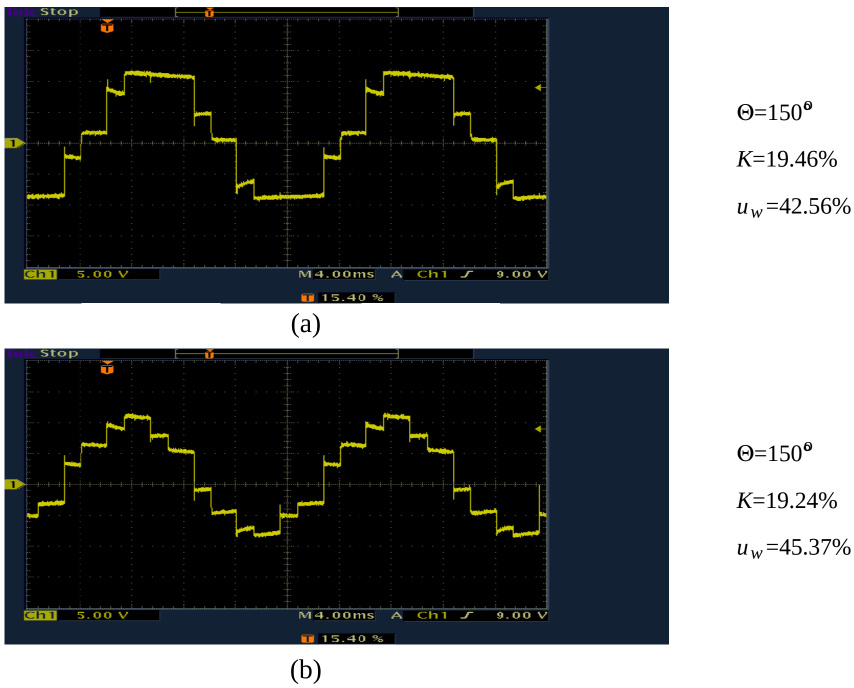

Figure 6: The output voltage waveform on the load for different configurations of transformer: (a) primary winding connected in wye, (b) primary winding connected in delta.

transformer. A load was wye connected three resistors. Figure 5 shows photo of the experimental setup and the Figure 6 phase voltage across the load.

The differences between the simulation and experimental results are mainly caused by a simplification in the theoretical model used in simulations (i.e., excluding a non-linearity of the transformer, ideal switching devices and a non-inductive load).

6. CONCLUSION

A concept of the high power static voltage source, which could be used as an external power source for ship's internal electrical network, was proposed in this contribution. After theoretical study, computer simulations and optimization, experimental model was created. In particular, the properties of the system in frequency domain were studied in order to minimize THD and Voltage Distortion level.

It is our opinion that the concept proposed is promising and we expect in the future to get further improvements, despite the actual system did not meet successfully all imposed by the law requirements.

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