

Laboratory studies of the operation of a single-phase solid-state transformer when operating from a wind turbine

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Abstract. The article describes a laboratory equipment for studying the operation of a single-phase solid-state transformer when operating from a wind turbine. Oscillograms of currents and oscillograms of voltages are given during the operation of a solid-state transformer from a voltage source. To simulate a wind turbine, the "actuating mechanism - generator" assembly was used. Wind gusts were simulated using a frequency converter. The key elements of the solid-state transformer - a dual active bridge - were controlled by the phase shift method. Critical points were found that could not be foreseen in a theoretical or simulation study. The experiment showed the perspective of using new technologies to maintain a stable output voltage frequency and voltage level.

1 Introduction

The rapid development of semiconductor technology, alternative energy and digital control systems contributed to the transition of classical electrical grids to smart grids. The use of modern power converters based on semiconductor technology makes it possible to increase the efficiency, reduce the weight and dimensions of the device, and also increase functionality. It will be necessary to introduce new devices and algorithms for the application of modern achievements in science and technology to increase the functionality of electrical grids. One of the devices that allows the transition to smart grids is a solid-state transformer (SST), which over the past few years has achieved impressive results and has already begun to be used in electrical grids [1]. The scope of SST application includes smart power grids [2], reactive power compensation [3], integration of non-conventional and renewable energy sources [4], power quality improvement [5], power supply for drives of rail transport [6-7]. Recent achievements in the development of the dual active bridge (DAB) are given in [8].

The aim of the work is to study the operation and search for weaknesses in the operation of a low power SST that receives an unstable voltage. The first stage is to study the operation of the SST, which has an open-loop control system. In further work, a system with a system with a feedback will be used to assess the quality of transient processes and the accuracy of the system.

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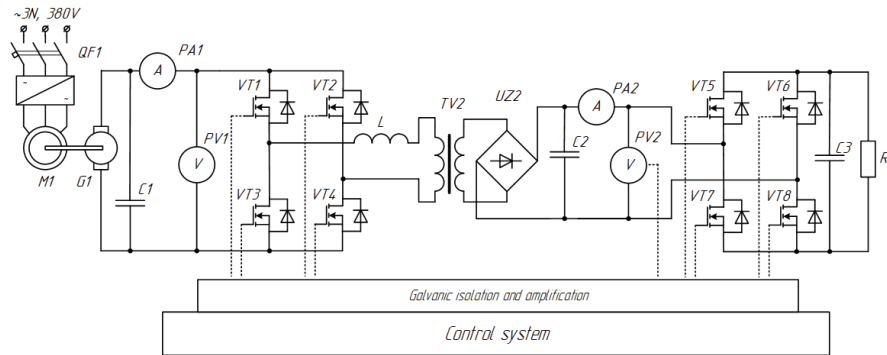


Fig. 1. Structural diagram of the laboratory testbed for the study of the operation of SST.

A laboratory testbed the schematic diagram of which is shown in Figure 1 was developed to study the operation of the SST. The possibility of operating the SST from a DC wind turbine is investigated using this testbed.

2 Development of a laboratory testbed

The testbed is based on the SST, which consists of a bridge converter and an output inverter. Because If the reverse direction of power transmission is not required, then, it is advisable to use a bridge converter instead of a dual active bridge for the purpose of saving. The bridge converter consists of an inverter is based on a bridge circuit of MOSFET transistors VT1-VT4. The resulting high-frequency voltage is applied to the UZ2 diode assembly, which converts the voltage to the fixed one. The inverters are assembled from eight IRF730PBFs rated at 400V and 5.5A. Active resistance R acts as a load. Capacitor C3 serves to filter the output voltage. The control is carried out by the following devices: PV1 and PA1 measure the input values of voltage and current, respectively; PV2 and PA2 measure voltage and current output values, respectively. There is a capacitor C2 to smooth possible output ripples of the converter. The inverters are assembled from eight IRF730PBFs rated at 400V and 5.5A. The KBU1010 diode bridge is rated for 10A and 1000V. Input capacitor is 1000μF, 400V; output capacitor is 100μF, 400V. The large capacitance of the input capacitor is worth it because the voltage ripples when rectifying a sinusoid is much higher than when rectifying a meander. The control was carried out using the STM32F407G-DISC1 debug board based on 32-bit ARM Cortex-M4 microcontrollers. The dead time was 1 μs.

An engine-generator assembly with a frequency-controlled primary AC motor was used to simulate a wind turbine. Induction motor AIR 80A2 220/380V with a power of 1.5 kW, rated rotational speed of 3000 rpm was chosen as the prime mover. A P21 DC generator with a power of 1.25 kW, rated rotational speed - 3000 rpm, voltage - 230 V was chosen as the main generator. A frequency converter Oven PCHV-1K5-V was used to change the rotational speed of the generator assembly. This frequency converter has the ability to control the rotational speed of the generator assembly flexibly according to various control laws (load and slip compensation), as well as control the rotational speed in a closed circuit according to signals from external sensors, that was used to simulate wind gusts. High-power resistance S5-35V (C5-35B)160 W 50 Ohm, a 10% resistor (analogue of FWEMRT-150 - fixed wirewound enamelled moisture resistant tubular resistors), connected in series and in parallel, as well as resistance rheostats 250 Ohm 1.4 A TETRON RSK-4-8 (A TETPOH PCK-4-8) were selected as the load of a solid-state transformer [9-10].

The control circuit, galvanic isolators and their power supply system are universal and can be used for a wide range of powers of the designed bridge converter. This is especially

important when designing a SST operating in a wide range of input voltage and various loads [11]. When removing the voltage, a voltage divider of 1:100 was used. A Troyka-Current Sensor with a sensitivity of 185 mV/A was used to measure the current. The following measuring equipment was chosen for testing:

- TETRON-MT92 digital wattmeter 600 V, 20 A, 12 kW;
- 10 kHz LCR meter TETRON-RLC10;
- - digital multimeter UT105;
- - digital oscilloscope,

– 2 channels AKIP-4115/3. Figure 2 shows the exterior of the SST, which is spaced and included in the experimental apparatus.

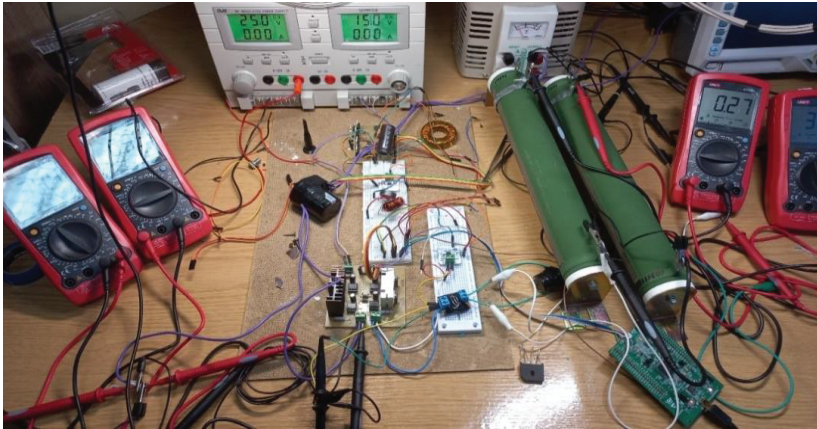


Fig. 2. Exterior of the experimental apparatus of a non-isolated bridge converter.

The windings of the pulse transformer are wound on a M2500NMS1 (M2500HMC1) ferrite core with dimensions of 45x28x8mm. The diameter of the primary winding wire is 1 mm, the diameter of the secondary winding is 2 mm.

3 Experiment

The bridge converter was controlled using a phase shift between transistors. Figure 3 shows the phase shift between the opening of TV1 and TV2. To implement the phase shift, the microcontroller timers are enabled through the Master/slave block. The master/slave block provides a block of base time that counts clock pulses, as well as a signal to control the direction of counting. This block basically provides control signals for the base time block. Due to this, it becomes possible to start the timer in slave mode by an external command during an interrupt, which provides a PWM shift by a given number of clock cycles of the master block counter. When using a phase shift of the PWM control signal by a quarter of a period, a three-level type of voltage is created at the output of the bridge converter, which is fed to the primary winding of the pulse transformer through an additional inductance. The timing diagrams of the current and voltage of the bridge converter are shown in Figure 4.

The switching of transistors VT3 and VT4 occurs in antiphase with respect to transistors VT1 and VT2, respectively. Dead time during switching is 1 μ s.

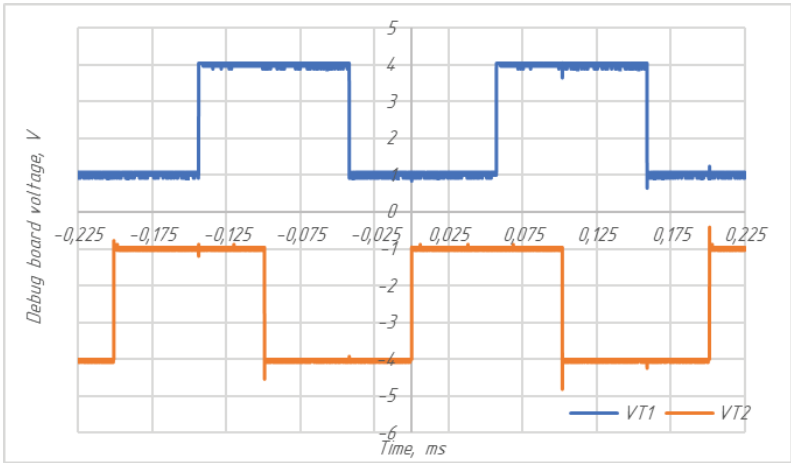


Fig. 3. Transistors switching of the bridge converter.

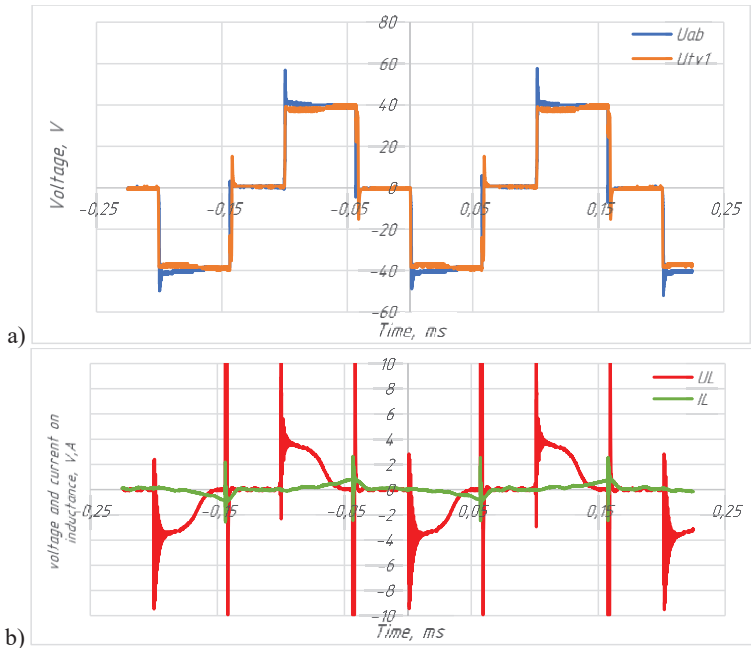


Fig. 4. Timing diagrams of the bridge converter: a) the voltage at the output of the bridge and the voltage at the input of the transformer; b) voltage and current on inductance.

The output voltage of a solid state transformer is shown in Figure 5.

The entire equipment was assembled after selecting and manufacturing all the necessary components. The STM32 debug board was programmed for testing with maximum load. Initial operation was tested with an open-loop control system. After working at the maximum load, it was determined that the temperature of the power elements (transistors, diodes, transformer, inductor, terminals) does not exceed 60 ° C. So there is no question of the need for forced cooling. In connection with this, it was decided not to install a cooler , but limited to radiators [11].

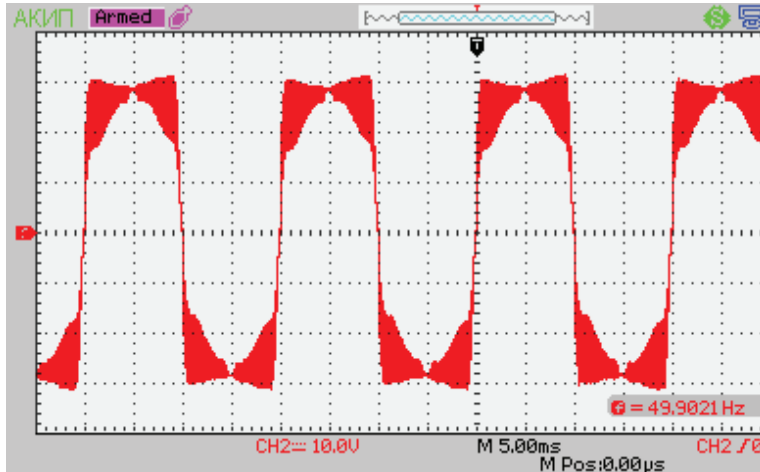


Fig. 5. Timing diagrams of the bridge converter: a) the voltage at the output of the bridge and the Equations and mathematics.

A block arrangement of a laboratory sample of a solid-state transformer was carried out after studying the operation on heating. Then, operation was also carried out at maximum load in continuous mode to study the heating of the components in the body. Experiments have shown that the system is stable.

An operation algorithm was developed and a program code was written for a debug board using the STM32CubeIDE program to study the operation of a laboratory sample. The operation of the controller was checked using an oscilloscope, and only after a detailed check, the controller was connected to the power section. The operation of a laboratory sample of a solid-state transformer was tested with a varying load and when changing input voltage. An inductor was selected experimentally, which would provide the highest efficiency of the solid-state transformer. The results of the operation showed that the performance of operation in both cases is approximately identical, but there is a slight overshoot. A sharp increase in current at the input of the HF transformer caused by insufficient additional inductance at high load was found among the problem areas. This can lead to failure of the solid-state transformer, so the introduction of a current limit on the primary winding is required. Also, large starting currents in the input rectifier were identified as problem areas due to the high capacitance of the smoothing capacitor. The issue of installing a voltage corrector after the input rectifier will be considered in future versions of the solid state transformer. The identified problems include a high level of electromagnetic interference appearing due to the operation of non-linear semiconductor devices at high frequencies. All this will be taken into account and if possible, adjusted at the next stage of work. The design documentation was adjusted based on the results of preliminary tests.

The carried out experimental research showed the perspective of using a solid-state transformer for the integration of non-conventional and renewable energy sources in electrical grids. Obtained acceptable results of using a solid-state transformer to bring the variable voltage of the current source to an alternating voltage of a given frequency and level, which has smaller mass and dimensions parameters and allows working within a wide range due to three-stage regulation. At the same time, a solid-state transformer is a complicated electrical complex located at the intersection of electrical engineering, power electronics, automatic control theory and microcontroller programming. It is necessary to continue serious research work to improve the design and control system for stable and reliable operation.

4 Conclusions

A laboratory testbed has been developed that simulates the operation of a wind turbine into a load using a solid-state transformer. The ways of further improvement of the solid-state transformer are shown. The developed installation allows making changes to the program code, replacing individual nodal elements, and take readings from various nodal points. Critical points were found that could not be foreseen in a theoretical or simulation study. These include a sharp increase in current at the input of a high-frequency transformer under insufficient load, large starting currents, the need for a voltage corrector after the input rectifier, and a high level of electromagnetic interference. Identified shortcomings will be taken into account and if possible, leveled at the next stage of work. The developed laboratory testbed for the study of the operation of a solid-state transformer has no analogues in Russia.

5 Funding

This work has been supported by the grants the Russian Science Foundation, RSF № 22-29-20094, <https://rscf.ru/project/22-29-20094/>

References

1. X.She, X. Yu, Eю Wang, A.Q. Huang, *Design and demonstration of a 3.6 kV-120 V/10 KVA solid state transformer for smart grid application*, in Proceedings of the 2014 IEEE Applied Power Electronics Conference and Exposition APEC 2014, Fort Worth, 16-20 March 2014, TX, USA (2014)
2. B.A. Avdeev, A.V. Vyngra, V. S. Sobolev, *Integration of Renewable Energy Sources into Smart Grids Using Converters Based on Solid-State Transformers*, in 2022 5th International Youth Scientific and Technical Conference Relay Protection and Automation, RPA 2022, (2022)
3. M. A. Hannan, Ker, Pin Jern, M. S. Hossain Lipu, Zhen Choi, Abd Rahman, Muhamad Kashem Muttaqi, F. Blaabjerg, *State of the Art of Solid-State Transformers: Advanced Topologies, Implementation Issues, Recent Progress and Improvements*, IEEE Access (2020)
4. B. Avdeev, A. Vyngra, S. Chernyi, Designs **5** (2020)
5. D. Shah, M. L. Crow., IEEE Transactions on Power Delivery **31(1)** (2016)
6. X. Zhang, Y. Xu, Y. Lon, S. Xu, A. Siddique, IEEE Access **7** (2019)
7. Q. Zhu, L. Wang, A. Q. Huang, K. Booth, L. Zhang. *7.2 kV single stage solid state transformer based on current fed series resonant converter and 15 kV SiC MOSFETs*. IEEE Transactions on Power Electronics, **34(2)** (2019)
8. A. Joshi, S. Nath, *Efficiency Comparison of Solid-State Transformer and Low-Frequency Power Transforme*, 2020 3rd International Conference on Energy, Power and Environment: Towards Clean Energy Technologies (2021)
9. K. Joshi, U. Balagopal, S. Sanjeevi et al, Design and Performance Analysis of Solid-State Transformer (2021)
10. NB Kadandani, M Dahidah, S. Ethni, An Overview of the Role of Solid State Transformer in Smart Grid. **1-6** (2021)
11. S. G. Chernyi, *Methods for ensuring fault tolerance of equipment based on reliability theory*, 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), Moscow and St. Petersburg, Russia (2018)