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DESIGN AND ANALYSIS OF SOLID STATE TRANSFORMER FOR SMART GRID

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ABSTRACT- Since solid-state transformers (SSTs) may get around a number of the drawbacks of traditional low-frequency transformers, they are becoming more and more significant in contemporary power systems. SSTs offer significant advantages like decreased size and weight, greater controllability, bidirectional power flow, higher power quality, and simple integration with smart grids and renewable energy sources by substituting power-electronic-based high-frequency conversion stages for heavy magnetic cores. This paper presents the design, development, and experimental evaluation of a low-voltage, three-stage Solid-State Transformer prototype implemented using Arduino microcontrollers. The proposed system follows a classical three-stage SST structure consisting of an AC–DC rectification stage, a high-frequency isolated DC–DC conversion stage employing a ferrite-core transformer, and a DC–AC inverter stage that delivers a regulated 50 Hz AC output. To improve modularity and ensure reliable real-time performance, the control system is divided between two Arduino UNO boards. One microcontroller is dedicated to generating high-frequency and low-frequency PWM signals, while the second handles voltage and current measurement, protection features, and IoT-based monitoring. The prototype effectively illustrates key SST characteristics such galvanic isolation, high-frequency operation, digital control, and modular expandability while operating at safe laboratory voltage levels below 48 V. This study promotes future research in sophisticated control techniques and wide-bandgap semiconductor technology while offering an inexpensive and instructive platform for comprehending SST ideas.

Keywords: Solid-State Transformer, High-Frequency Isolation, Arduino Control, Power Electronics, Three-Stage SST, Smart Grid

I. INTRODUCTION

Electrical power systems across the globe are undergoing rapid transformation driven by the increasing penetration of renewable energy sources, the proliferation of electric vehicles, the emergence of microgrids, and the growing demand for intelligent and flexible power distribution. Conventional power transformers, which operate at the fundamental grid frequency of 50/60 Hz, have been a cornerstone of electrical infrastructure for more than a century. Large size, hefty weight, set voltage transformation ratios, lack of controllability, and inability to actively participate in power quality management are some of the fundamental disadvantages that these transformers face despite their robustness and dependability. Using developments in power electronics, digital control, and high-frequency magnetics, Solid-State Transformers (SSTs) have become a viable substitute for traditional transformers.There is a growing need for accessible and safe SST prototypes that can demonstrate fundamental operating principles without the risks associated with high-voltage operation. Microcontroller-based implementations, particularly those using Arduino platforms, provide an attractive solution due to their low cost, ease of programming, wide community support, and suitability for rapid prototyping. Although Arduino-based systems cannot match the performance of industrial-grade controllers, they are more than adequate for demonstrating core SST concepts at low power levels. We present the design and implementation of a three-stage SST prototype controlled using Arduino microcontrollers. The system uses two Arduino UNO boards in a modular control architecture and runs at low voltage levels appropriate for laboratory testing. While the second microcontroller manages sensing, protection, and Internet of Things-based monitoring, the first microcontroller is only focused on PWM generation for the power conversion stages, guaranteeing steady and deterministic switching.

II. METHODOLOGY

Prior to you, the suggested three-stage Solid-State Transformer (SST) design process is set up to replicate the basic ideas used in contemporary SST research and industrial development, all the while preserving safe operating conditions and the viability of laboratory-scale implementation.. Unlike conventional transformers that rely on low-frequency magnetic coupling, the SST employs power-electronic converters and high-frequency magnetics, necessitating a systematic and multi-disciplinary design approach that encompasses power electronics, control systems, magnetics, thermal considerations, and digital implementation. This structured approach ensures that each subsystem is independently optimized while maintaining overall system coherence.SST architectures are commonly classified into three categories: single-stage, two-stage, and three-stage configurationsThe third stage reverses the DC voltage back to AC at the required output frequency and voltage level, while the second stage functions as an isolated DC–DC converter using a high-frequency transformer. With this arrangement, input power quality, isolation, voltage scaling, and output voltage regulation may all be independently controlled. However, full-bridge or push-pull converters provide a more straightforward and affordable option for low-power prototypes and instructional systems.. Control strategies for SSTs range from simple open-loop modulation schemes to advanced model predictive control, adaptive control, and artificial intelligence-based approaches. Industrial and research-grade SSTs often rely on DSPs or FPGAs to achieve high switching frequencies, precise timing control, and real-time protection. Nevertheless, several studies have demonstrated that microcontroller-based control is sufficient for low-power SST prototypes and educational demonstrators, provided that switching frequencies and power levels are kept within safe limits

III. MODELING AND ANALYSIS

Rectification stage

In this stage the 24 VAC is converted into 30- 36 VDC using diode configuration in the full bridge. The Inductor and capacitor are used at the input supply to improve power quality and protect the system. The inductor reduces current ripple, limits inrush current, and suppresses harmonics, while the capacitor smooths voltage fluctuations and absorbs spikes. Together, they form an LC filter that provides smooth, stable input power to the converter. The used is 6A10 which has high average forward current rating of 6 A and repetitive reverse voltage of 1000 V. It has a forward voltage drop of about 1 to 1.1 V.

- Isolation stages

In the DAB stage the primary stage converts the VDC converted by rectification stage into the VAC. In middle the High frequency transformer is use for the Isolation purpose. In the second stage of DAB the High frequency

VAC is converted into Low voltage DC by using MOSFET. In both stage the IRF244N MOSFET is use which has a drain source voltage rating of 55 V and can handle a continuous drain current of up to 49 A. It has a low on state resistance (RDs(on)) of about 0.022 ohm resulting in low conduction losses and improve efficiency. It has a gate source voltage of +-20 V.

- High frequency stage

The High-Frequency Transformer (HFT) is a main component of the DC–DC conversion stage in a Solid-State Transformer. Its main function is to provide galvanic (electrical) isolation between the input and output sides.It allows large voltage and current transformation ratios, which are required in smart grid applications. The HFT works at high frequency in the range of KHZ . We have use 20 KHZ frequency transformer in this stage. Due to Operating is at high frequency it reduces the size and weight of the transformer. Thin Grain-Oriented Electrical Steel (GOES) is selected for the HFT core for the advantage such as high saturation flux density, Good performance at high temperature and Litz wire is commonly used which reduces skin effect, reduces proximity effect. The turns ratio in high frequency transformer is given by,

VDAB1/ VDAB2

Where,

VDABI High Voltage side DAB voltage

VDAB2 Low voltage side DAB Voltage

- Inverter section

In inverter section the 30-36 low VDC supply coming from secondary of DAB is converted in 24VAC with the help of inverter section. It uses P55NF06 N-channel power MOSFET connected in Full bridge configuration. It handles 50–55 Ampere high current with maximum drain source voltage of 60 V.

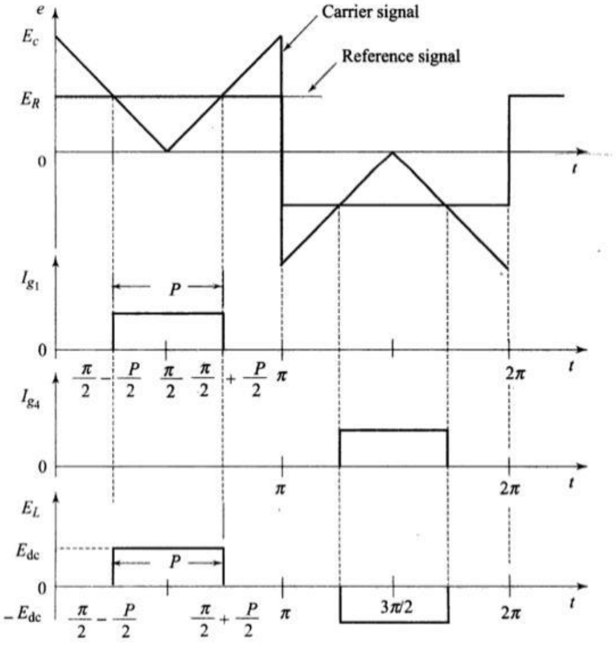
- Arduino UNO

This is used microcontroller development board based on the Atmega328P microcontroller. It operates at 5V and runs with a 16MHZ crystal oscillator, providing stable timing for control applications. The controller has 14 digital input/output pins and 6 pins can be used as PWM output and 6 analog input pins for sensor interfacing. Pin 10-13 are used for primary DAB, Pin 6-9 secondary DAB and Pin 2-5 Inverter Section are used for PWM control.

- Switching of DAB section

The switches in each H-bridge are triggered in diagonal pairs. Both bridges operate at the same switching frequency, but a controlled phase shift is introduced between the primary and secondary square waves. This phase shift creates a voltage difference across the transformer leakage inductance, which determines the magnitude and direction of power Transfer. The phase shift is created by square wave triggering with the help of IR2110 Gate Driver IC . It works as a high side and low side gate driver for MOSFET through HIN and LIN pin.

- Switching of inverter
- In single pulse width modulation, only one voltage pulse is generated in each half cycle of



the output waveform. The width of this pulse is varied to control the inverter output voltage. To generate the gate signals for the switching devices, a rectangular reference signal with amplitude Vr is compared with a triangular carrier wave having amplitude Vc. When Vr > Vc, gate pulses of width 2d are produced for MOSFET. When these switches are turned ON, a modulated AC output voltage with amplitude Vs and pulse width 2d is generated.

IV. RESULTS AND DISCUSSION

Because it is more flexible and controllable than single-stage and two-stage options, a three-stage SST architecture is chosen. The input, isolation, and output stages can all be functionally decoupled thanks to the three-stage arrangement, which permits independent optimization and a clear illustration of SST concepts. The general architecture is made up of:
Stage 1: AC–DC Conversion: Creates a reliable DC link from low-frequency AC input.

Stage 2 – High-Frequency Isolated DC–DC Conversion: Performs voltage transformation and galvanic isolation using a high-frequency transformer.

Stage 3 – DC–AC Conversion: Generates a regulated low-frequency AC output using inverter-based techniques.

This architecture closely resembles that employed in medium- and high-voltage SSTs used in smart grids and traction systems, thereby ensuring the relevance of the proposed prototype to real-world applications. For AC–DC Conversion, A low-voltage 24 V AC input is rectified using a full-bridge rectifier. The rectified voltage is filtered using a DC link capacitor (15000 µF, 63 V rating) to provide a stable DC bus of approximately 32–36 V. A full-bridge MOSFET inverter converts DC to high-frequency AC at 25 kHz. A ferrite-core transformer provides galvanic isolation and voltage scaling. The secondary is rectified using fast recovery diodes (6A10) and filtered using a DC capacitor. Key design considerations:

- Switching frequency: 25 kHz
- MOSFETs: IRF3205 / IRFZ44N
- Gate driver: IR2110 / IR2103
- Ferrite transformer with proper insulation

For the DC–AC Inversion, A full-bridge inverter using SPWM generates a 50 Hz AC output. An LC filter attenuates high-frequency harmonics to produce a near-sinusoidal waveform. The SST prototype was experimentally evaluated under laboratory conditions using resistive and light inductive loads. Stage-wise testing confirmed correct operation of each power conversion block. The AC–DC stage produced a stable DC link voltage, the high-frequency isolation stage successfully transferred power across the ferrite-core transformer, and the DC–AC stage generated a stable 50 Hz output voltage with reduced harmonic distortion after filtering.

V. CONCLUSION

We have presented the complete design, implementation, and experimental validation of a low-voltage, three-stage Solid-State Transformer (SST) prototype controlled using Arduino microcontrollers. The proposed system successfully demonstrates the fundamental operating principles of modern SST architectures, including power-electronic-based voltage transformation, high-frequency galvanic isolation, modular power conversion, and digital control, while operating within safe laboratory voltage limits. A classical three-stage SST configuration was adopted, consisting of an AC–DC conversion stage, a high-frequency isolated DC–DC conversion stage, and a DC–AC inversion stage. This architecture enabled clear functional decoupling between input conditioning, isolation and voltage scaling, and output voltage synthesis. The design methodology closely mirrors that of practical medium- and high-voltage SST systems reported in the literature, thereby ensuring that the proposed prototype remains relevant to real-world applications despite its reduced power rating

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