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DESIGN AND OPERATION OF A SOLID-STATE TRANSFORMER FOR INTEGRATION OF RENEWABLE ENERGY SYSTEMS

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Abstract. Renewable energy-based grid integrations in distribution systems cause changes in the energy structure of the grid such as load flow, short circuit and protection coordination. Today, conventional transformers are insufficient in meeting the needs of loads with different profiles and in connection with renewable energy sources such as solar and wind to the grid. Additional mechanisms are needed to overcome power quality problems, especially voltage rise and fall, fraying, or harmonics. With the advances in semiconductor technology, power electronics has emerged as a promising solution to dealing with the problems of complex power systems. Solid-state transformer (SST) is a novel technology that can affect developments in many fields such as renewable energy systems, smart grids, distribution tail systems for flexible power conversion between medium voltage distribution and low-voltage customer side. Compared to the conventional transformers, SSTs provide reactive power compensation, simple connection of renewable energy sources and battery systems, power factor correction, galvanic isolation, smart protection, harmonic control and frequency conversion. As a result, the integration of renewable energy plants to the electrical grid creates big challenges in terms of harmonics, power flow control, power factor correction, isolation and smart protection. Thus, SSTs will play a significant role in future grid topologies. In this study, modeling and analysis of a solid-state transformer for a grid-connected solar PV plant are carried out with MATLAB/Simulink. The power analyses of the proposed system are examined thanks to the simulation study. This analysis would be a significant contribution to the development and implementation of renewable energy-based applications of the SSTs.

Keywords: solid-state transformer, smart grid, smart transformer, solar PV.

INTRODUCTION

Conventional low-frequency transformers are a significant part of the transmission and distribution of electricity in power systems. These transformers, on the one hand, provide electrical insulation between the connection points, on the other hand, they also change the voltage levels in order to achieve voltage matching at the input/output ends. Low-frequency transformers can be used in electrical networks for a long time due to their simple structure, high efficiency and safety. However, depending on the power needed, the dimensions of these transformers increase and their weight increases due to the core and winding structures. This makes it difficult to transport and increases the cost by complicating production and installation. On the other hand, these transformers have the disadvantage that they are not suitable for use with technologies such as DC distribution systems, distributed generation sources and energy storage units. SSTs as an alternative to conventional transformers have begun to be investigated.

SST is a potential competitive intelligent electronic device that enables bi-directional power flow, reactive power compensation, harmonics reduction, and many others. These transformers are the combination of high-powered semiconductor components, control circuitry and conventional high-frequency transformers. Solid-state transformers can be used for different applications such as renewable energy-based power grid, future smart grid developments, power electronic conversion technology, and others. Unlike a traditional transformer, solid-state transformers are performed not only to transform ac electricity, but also to transform dc electricity, or to couple ac and dc electricity. Regarding the working principle of an SST, the three-stage topology provides both AC-DC and DC-AC conversion. During the conversions, voltage control, reactive power compensation and power factor regulation are achieved. DC-DC conversion part is the isolation stage of the SST. Also, the bidirectional power flow is provided thanks to voltage control. The power transfer at a high frequency has advantages of high efficiency, small size and weight, low cost. The faster switching speed of solid-state devices would in turn make it easier for a utility to power sources feeding into the grid because they provide more transformers controlling and fine-tuning power quality.

In the past five years, the concept of the solid-state transformer (SST) has been very popular, and extensive research has been done for applications in power systems. Studies are presented by examining the literature. When research and development studies on the solid-state transformer or smart transformer are examined in detail in the literature, it is observed that they are used in different fields.

De Carne (2016) proposed a soft load reduction method that reduces the voltage control and load consumption of the solid-state transformer under overload. With the proposed technique, it has been observed that the load provides effective power consumption reduction without separating any load in the network (De Carne et al., 2016).

VC (2016) controlled the active power flow between the electricity grid and micro-grid systems with minimal loss. The study was presented by supporting the simulation results made in MATLAB/SIMULINK. The voltage-based control of the smart transformer allows the control of active power flow at the common connection point between the electricity grid and the micro-grid (VC et al., 2016).

Leibl (2016) presented an optimization and thermal model of the transformer used to design a 166 kW/20 kHz transformer prototype operating at 99.4% efficiency with a power density of 44 kW/dm^3 (Leibl et al., 2016).

Andresen (2016) conducted thermal stress analysis for the modular multi-level converter in the medium voltage phase of smart transformers. Even if the thermal stress caused by network faults is higher than normal working time, no significant decrease in life has been observed (Andresen et al., 2016).

Zou (2017) proposed a frequency adaptive control scheme based on fractional sequential repetitive control and frequency adaptable phase-locked loop in their study. Serial-resonance DC-DC converter provided a fast frequency matching feature to adapt highly to variable frequencies (Zou et al., 2017).

Costa (2016) proposes a reconstruction topology for Serial Resonance DC-DC converter in case of failure in a semiconductor in their study. Using the proposed topology, the full-bridge based Serial-Resonance DC-DC converter is presented in detail that the half-bridge topology can be reconfigured to keep the converter running in case of a switch failure such as an open circuit or short circuit (Costa et al., 2016).

Zhu (2019) proposed a parallel connection of a solid-state transformer based smart transformer and a conventional power transformer to support voltage amplitude and improve grid current quality (Zhu et al., 2019).

Huber and Kolar (2017) presented the effective usage application area of the solid-state transformers. The integration of uncontrolled distributed energy generation systems such as photovoltaic and wind turbines leads to deterioration in power quality. The power electronics-based smart transformer can provide system voltage and reactive power control by integrating into the distribution network without the installation of additional devices. Therefore, solid-state transformers are the key components for the solution of these problems in PV and wind turbine applications (Huber & Kolar, 2017).

Gao (2017) determined the voltage profile of the smart transformer and safe operating limits for 25-bus simulation studies fed with medium voltage modeled in PSCAD/EMTDC. In the light of the data obtained from the simulations in PSCAD, the efficiency of the smart transformer was observed to control the voltage profile within safe operating limits without integrating any additional devices and increasing the cost (Gao et al., 2017).

Zhu (2017) presented the two-level single-stage topology and the medium voltage solid State Transformer with efficiency analysis results, which reaches 97% levels based on 15 kV SiC MOSFETs in detail (Zhu & others, 2017).

Madichetty (2018) developed a smart transformer model with a high switching frequency in their study. This proposed model is controlled by a conventional voltage control technique and a newly proposed power control technique. Besides, control methods are used to develop applications for integrating electric vehicles into a DC micro-grid system with a battery charging station (Madichetty et al., 2018).

Thanks to the study to be carried out, all stages from the design of a local solid-state transformer to an industrial product will be analyzed by simulation analysis. The availability of this product in the renewable energy area will be presented. Also, it stands out as a unique feature of the proposed solid-state transformer, providing significant improvements in critical parameters such as network reliability and power quality.

MATERIAL AND METHODS

When the searches studied in the last 5 years are examined, it is considered to select a three-stage configuration that includes different AC-DC, DC-DC and DC-AC stages according to the literature review. The most important part of solid-state transformer design is the selection of a suitable converter model to ensure power flow control and system reliability. In order to obtain the MATLAB/Simulink model effective transformer model, a pre-simulation study was conducted based on a three-stage topology. The preliminary study is shown in Figure 1.

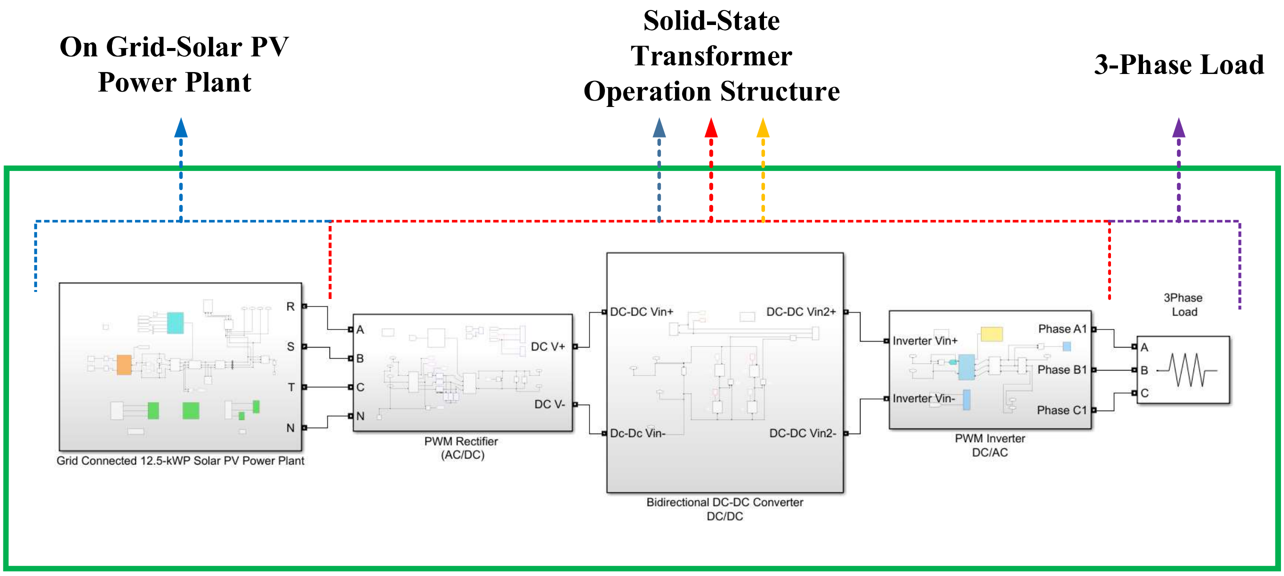

Figure 1. **Renewable energy-based three-stage solid-state transformer topology.**

The grid integration of renewable energy, which is widely used in smart grid applications, is very important. Therefore, the input energy of the proposed solid-state transformer will be supplied by renewable energy. Solar panels are used as input energy. After the transformer design is realized, the wind turbine system as well as solar panels are expected to be included in the network integration. In the preliminary simulation, the solar panel consists of a pulse width modulating inverter, a bidirectional DC/DC converter, a pulse width modulated inverter and a 3-phase load. Controllers of all systems are applied to achieve effective power regulation. In the pre-simulation studies, the most preferred bidirectional DC/DC converter model was selected and simulated in the literature. Simulation studies will continue until the appropriate converter model is obtained in active power control and voltage regulation.

The solar power plant, which is directly connected to the grid, is connected to a grid through a three-phase converter to obtain a pure sine 380-V AC voltage. A detailed model of the 12.5-kWP solar PV plant with 480-V DC open circuit voltage is shown in Figure 2. The figure shows a detailed model PV plant connected to a grid via a three-phase converter to obtain 380-V AC voltages. The solar PV array comprises 5 parallel strings. Every string has 6 solar PV panels connected in series. The conversion methodology is realized by using a 3-level IGBT bridge inverter. Harmonics are occurred by the IGBT bridge. In order to provide the filtering operation for the harmonics, a filter capacitor C and an inverter choke RL are used by calculating the specific values of them. The connection between the inverter and distribution grid system, a 250-VA 380/380-V wye connected three-phase transformer is used.

With the help of a pulse width modulation (PWM) rectifier, 380V AC energy is converted into 400V DC voltage. The combination of a solar PV power plant or a renewable energy plant with a distributed power grids and battery storage systems requires that the front-end rectifier runs with bidirectional power flow and simultaneous power factor coordinately. Therefore, this part should check a DC link. Also, it eliminates harmonics caused by the current distortions on the joint side. Therefore, a modular PWM rectifier topology is selected for the blocking capabilities of current power switches in MV levels. The PWM converter structure is presented in detail in Figure 3. The PWM converter is a regenerative converter and works on the principle of force modification techniques. Since different voltages are connected to the bus system compared to the reference voltage in DC bus feeds, the DC voltage should be constant. A variety of control methods are available according to the switching model of the converter. These methods enable error pulses produced by the comparator. Therefore, the current and voltages are controlled thanks to DC link voltage. The reference and actual values of the voltages are compared by the comparator. While the error pulse states positive, DC capacitors can be discharged. As a result, the six pulses can be generated for power switches. Also, the phase shift operation is realized and continuous power flow is provided from AC-side to DC-side. While the error signal states negative, the DC capacitor is overcharged. At this stage, the control block enables the capacitor discharge.

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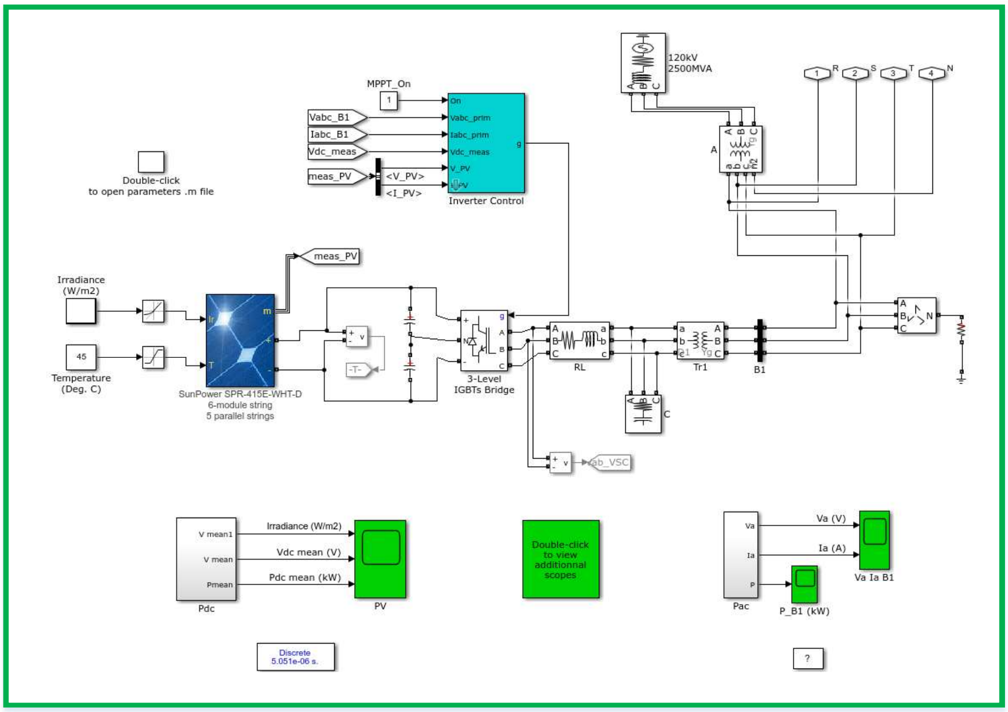


Figure 2. **Grid-connected solar power plant controller and its design.**

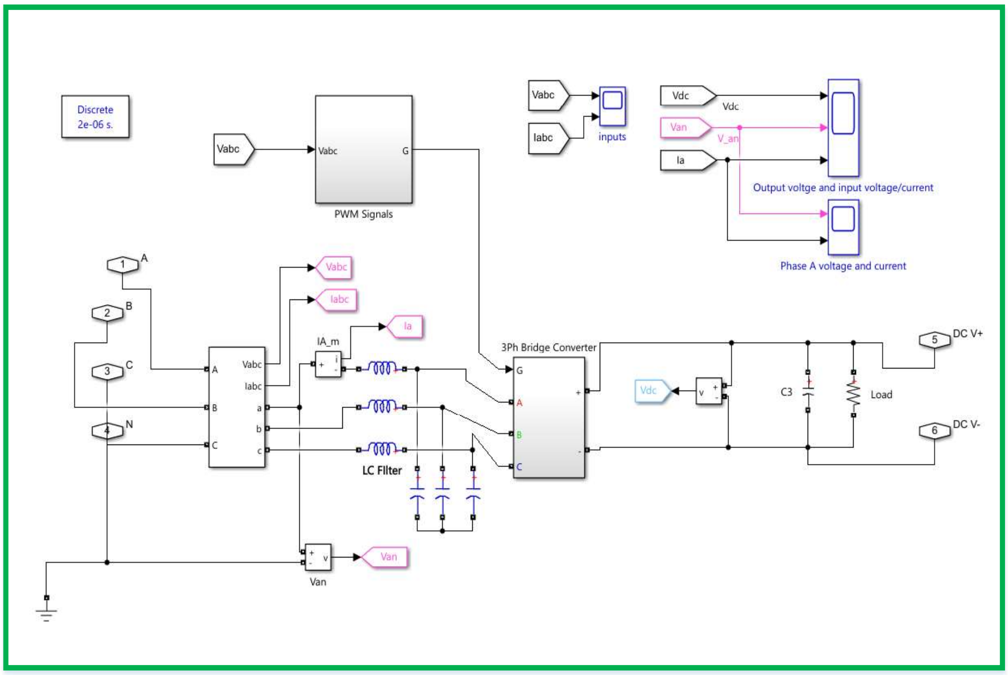


Figure 3. **PWM rectifier structure.**

Providing a nominal level of constant voltage is an important issue for utility grid and end-users. The generated voltage fluctuates continuously in the renewable energy-based DC bus systems because of changing weather conditions characteristic of the environment and changing the power situation of the connected loads. This case results in a voltage imbalance in the system. In this study, a bidirectional converter was first tested according to the voltage of the network to overcome the problem mentioned above. The proposed control technique has been simulated. 400-V DC has been applied in the network and the results have been analyzed. Bidirectional power controlled converter has been the most preferred model in the literature with its effective performance in reducing current and voltage harmonics and keeping the voltage constant. Figure 4 shows the bidirectional converter model with a simulation study.

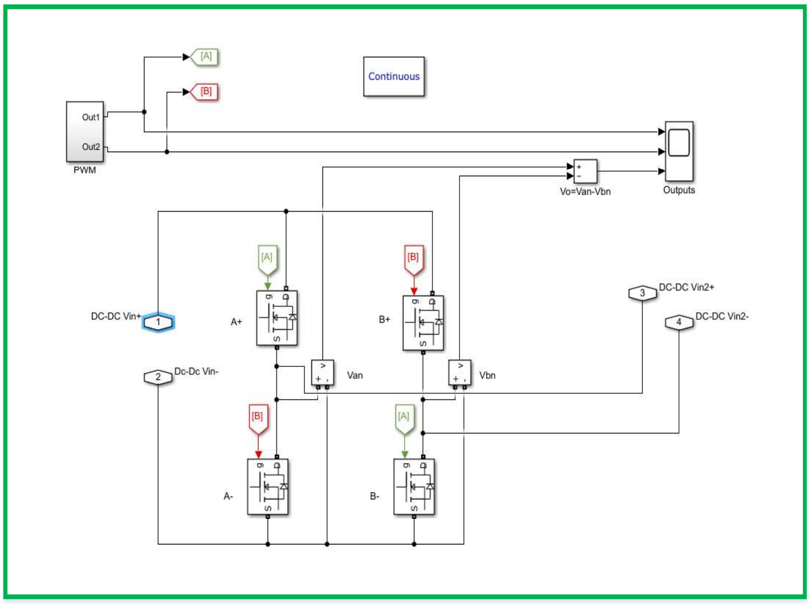


Figure 4. **The proposed DC-DC bidirectional converter model.**

Bidirectional converters provide bidirectional energy conversion between two DC bus bars. They have different usage areas such as renewable energy sources, fuel cell energy systems, electric vehicles, uninterruptible power supplies and DC motor applications. The energy obtained from solar energy systems can be transferred directly to the load or stored in batteries to prevent the loads from being de-energized when solar energy is not sufficient. Accordingly, to store the energy obtained, the batteries must be charged, and the batteries must be discharged to provide energy to the loads in the absence of sun. To realize this process, bidirectional DC-DC converters are required. The main features of the bidirectional converter are the ability to dynamically share constant power demands and transient instantaneous power demands between batteries and capacitors separately and dynamically, the possibility of flexible power flow between different battery groups, the realization of capacitor charge-discharge processes without disturbing normal operation, and thus, renewable energy-based It is to provide flexibility for increases in power and energy values in storage systems. Thus, bidirectional DC-DC converters are gaining more and more attention in academic research and industrial applications. Power capacity with switches has higher than any other unidirectional topologies. The conversion efficiency is approximately 95%. Therefore, these converters are useful in high power and hybrid energy system applications. Single-phase shift is the method commonly used in the proposed converter topology. This technique has advantages: small inertia, high dynamic and smooth switching convenience, but the power flow suffers from the leakage inductance of the transformer.

The 3 Phase PWM Inverter is a voltage source inverter that uses pulse amplitude modulation switching techniques and generally has a fixed size DC input voltage. Inverters work similar to the operating logic of AC - DC rectifiers, but in the opposite direction. While inverters provide this function, alternating current is obtained at the desired voltage, power and frequency values. The most important advantage of inverters is that harmonics in the output waveforms are reduced without increasing the switching frequency or reducing the power output of the inverter. The modulation strategies are the key parts for all inverters to reduce switching and harmonic losses. Pulse Width Modulation has several techniques. In this design, the Sinusoidal Pulse Width Modulation (SPWM) technique was used to control the inverter as it can directly control the output voltage and output frequency according to the sine functions, as shown in Figure 5. SPWM is the usable method for digitizing the power in power electronics so that a series of voltage pulses can be generated by turning the power switches on and off. In the SPWM method, a high-frequency carrier triangle signal and modulating reference marks are compared. Asymmetric voltage shapes and low band harmonics occur in low-frequency switching. In order to prevent this situation that may occur in the SPWM, a method that can switch over the over-modulation range has been developed. In inverters in which this type of modulation is used, the voltage at the input is almost constant. Because this voltage is provided by rectifying the grid voltage using an uncontrolled rectifier. Therefore, the inverter has to adjust both the frequency and the amplitude of the output voltage. This adjustment process is provided by pulse width modulation. Both the amplitude and the frequency of the output voltage of an inverter need to be adjusted. While these are set, the output voltage should be as close to the sinus form as possible. To obtain a sinusoidal voltage at the desired frequency, the frequency of the control signal must be the desired frequency at the output.

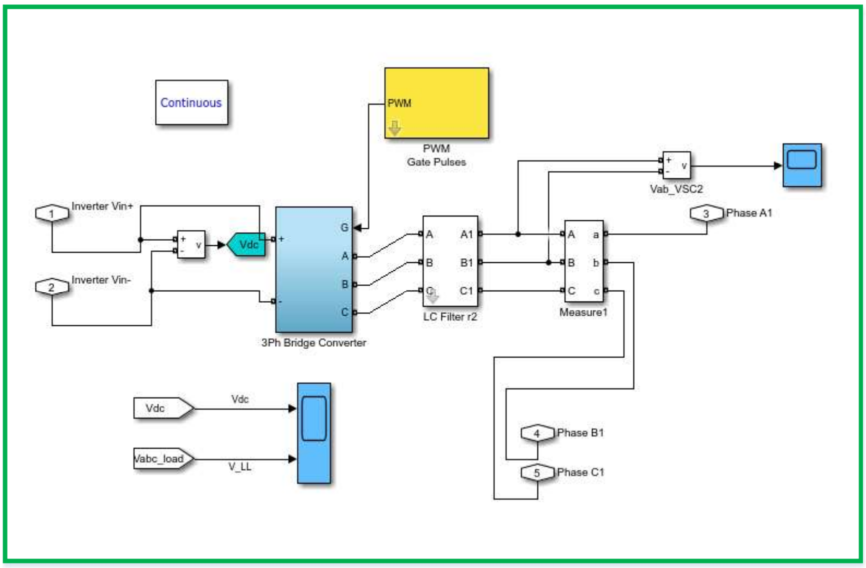


Figure 5. **Inverter model with sinusoidal pulse width modulation technique.**

RESULTS AND DISCUSSIONS

Preliminary simulation results are presented in detail. For the ideal case, the generated voltage of the solar power plant, the voltage generated by the solar PV plant in different weather conditions, the inverter side - the converted voltage current, the grid voltage, the inverter phase voltage and the system frequency are as shown in Figure 6.

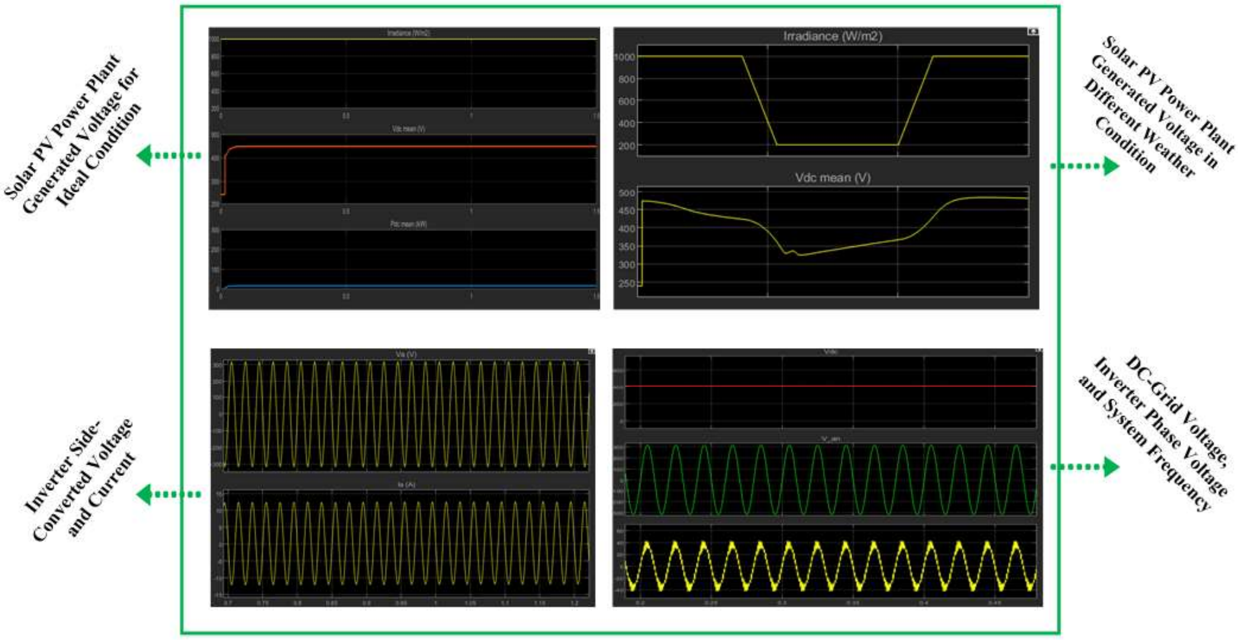
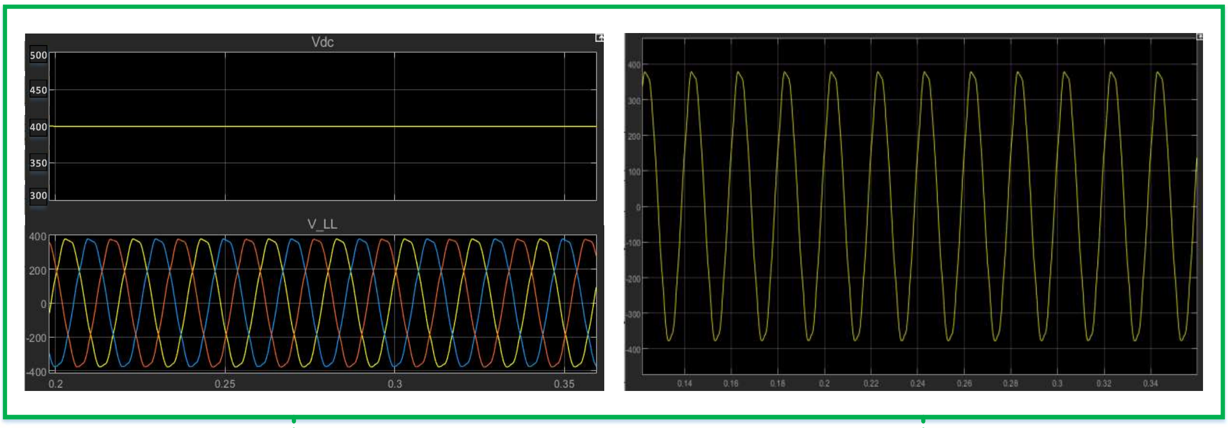


Figure 6. **The conversion of voltages generated from the PV plant to alternating current and direct current forms.**

The power generated from the PV plant has been converted to alternating current and connected to the grid. The network voltage level has also been rectified to a medium voltage level. Power flow is provided in two directions thanks to the bidirectional converter. In the last stage, conversion to 50 Hz frequency 380-V voltage level was achieved. The bidirectional converter and the PWM inverter output for the desired voltage level are successfully ready for use as shown in Figure 7.



DC-DC Bidirectional Convertor Voltage and Converted Phase Voltage via PWM Inverter

Final Stage of the Voltage for Residental Customers

Figure 7. **Realization of bidirectional conversion for medium voltage networks and obtaining the desired voltage with PWM inverter.**

CONCLUSION

Power quality problems are occurred by increasing the energy demand day by day. This case results in grid failures such as over current, harmonics, voltage imbalance and power factor deterioration. Solid-state transformers are emerging technology to prevent the system from failures and to make the system more reliable. In this study, it is aimed to determine the rectifier, inverter and converter structures required to produce a solid-state transformer by preliminary simulation studies. In the simulation study, the proposed converter structures provide the system reliability by using 3 stage topologies for AC and DC networks. For further studies, serial resonance converter (SRC), double half-bridge (DHB), double active bridge (DAB), asynchronous quad active bridge (AQAB) converter and synchronized quad active bridge (SQAB) converter models will be used as the superior performers. These converters can achieve soft switching, high efficiency and power density. Therefore, the most efficient SST structure will be determined by designing and analyzing the converter models with simulation studies.

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