On-Grid Photovoltaic System Using A Solid-State Transformer

Hanny H. Tumbelaka, *IEEE Member*
Department of Electrical Engineering
Department of Engineer Profession Education
Petra Christian University
Surabaya, Indonesia
tumbeh@petra.ac.id

Handry Khoswanto
Department of Electrical Engineering
Department of Engineer Profession Education
Petra Christian University
Surabaya, Indonesia
handry@petra.ac.id

Stephanus A. Ananda
Department of Informatics
Petra Christian University
Surabaya, Indonesia
ananda@petra.ac.id

Thiang Hwang Liong Hoat
Department of Electrical Engineering
Petra Christian University
Surabaya, Indonesia
thiang@petra.ac.id

***Abstract*—This paper explains a single-phase on-grid PV system employing a solid-state transformer (SST) which consists of a DC-AC converter, a high-frequency transformer, a simple rectifier, and a Voltage Source Inverter (VSI). The DC-AC converter converts the PV panel output voltage to a high-frequency three-level square wave required by the transformer operation. The pulse width of the square wave determines the PV operating points. The high-frequency transformer provides voltage level matching and galvanic isolation between the PV panels and the grid. While a simple rectifier produces a DC bus voltage for the VSI. The VSI has a grid current controller and a DC bus voltage controller to regulate the electrical power flow of the grid, the load, and the PV panel. Computer simulation results prove that the PV power can be delivered to the load and the grid through SST, while the grid current is kept sinusoidal and in phase with the grid voltage.**

Keywords—Solid State Transformer, On-Grid PV, Converter, Voltage Source Inverter

I. Introduction

Solar panels have been used as an alternative energy source. Installation of solar panels can generally be on-grid and off-grid. Off-grid installation can become independent power sources. Electrical energy from the solar (PV) panel is only fed to electrical loads as well as batteries as an energy storage. Off-grid installation is ideal for remote areas. In some cases, the off-grid PV system can serve as a backup power supply in the event of a grid failure. Meanwhile, on-grid installation means being connected to the grid. Excess electrical energy from the PV panel after being consumed by electrical loads can be delivered to the grid. Thus, it does not need batteries or other energy storage. The grid behaves as a virtual storage system that allows sending or receiving electricity when needed. The installation and maintenance costs are reduced. For the on-grid PV system, a device usually called a grid-tie inverter is required. The inverter converts DC into AC and can be synchronized to the grid [1][2].

The on-grid PV system must be compatible with the electrical grid. On the other hand, the voltage of the PV panel and the grid is different. In addition, The PV panel needs to have galvanic separation (isolation) from the electrical network for safety and signal integrity reasons. Adjusting the voltage difference can be done with a transformer on the AC side [3] or a boost converter on the DC side [4]. Meanwhile, the isolation can be resolved using a transformer. The transformer works to increase or decrease the voltage and current levels through electromagnetic induction coupling. Generally, the existing transformer operates at a grid frequency (50/60 Hz). For the power distribution transformer, it has a large volume and weight. Moreover, the transformer cannot be directly attached to the PV panel that works with DC voltage. The DC-AC converter is needed as an interface between the DC output voltage of the PV panel and the AC grid voltage.

The development and application of a solid-state transformer (SST) are growing. The SST integrates power electronics converters and a high-frequency transformer [5][6][7] to form an AC-AC converter like a conventional transformer. Fig. 1 shows several SST configurations. The high-frequency transformer has a smaller volume and weight than the conventional transformer. The use of SST generally replaces the existing transformer (conventional, $f = 50/60$ Hz) in power distribution networks [8][9], where the medium voltage of 20 kV is stepped down to a low voltage of 220/380 V to supply electricity to customers.

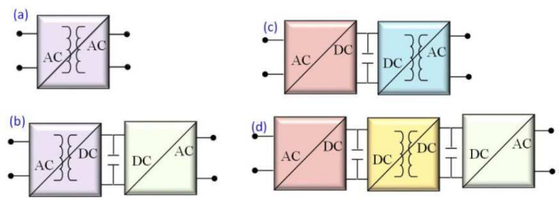

Fig. 1. Configuration of SST a) single stage, b) and c) two stages, d) three stages [6]

Looking at the SST configurations, they may be used as an innovative solution to overcome the on-grid installation problems mentioned above. However, SST is commonly used in distribution networks and connects the electrical network to the load. Meanwhile, in the on-grid PV system, SST will be used to connect the electrical network to the PV panel, which is a source. Moreover, the PV panel generates DC electricity. Therefore, the problem is how to develop SST so that it can function as a coupling between the grid and the PV panel. SST has to provide grid compatibility to the PV panel while maintaining the power quality of the grid. This paper proposes the proper SST configuration so that it is suitable for on-grid PV systems to deliver the PV power to the grid and the load.

This work was supported by The Ministry of Education, Culture, Research, and Technology, Indonesia under Grant 183/E5/PG.02.00.PL/2023

Several researches have been done on the application of SST for the on-grid PV system. In [10], the system adds a bidirectional buck-boost converter to obtain the PV power. Another system, the SST topology uses a multilevel H-bridge for LV inverters, and MV rectifiers and inverters [11].

This paper focuses on an attempt to modify SST into a DC-AC converter for on-grid PV applications. Section II describes the operation principle and analysis of the SST configuration which consists of a DC-DC converter and a Voltage Source Inverter (VSI), as well as their controllers. To verify the concept, computer simulation using PSIM has been carried out and presented in Section III. The results focus on the area of the PV output side and the grid side. The conclusions are written in Section IV.

II. On-Grid Photovoltaic Configuration

From Fig. 1, the selected Solid State Transformer (SST) configuration is 1(d) and has three stages. Since PV panels produce DC electricity, SST has to be modified to interface the DC output voltage of the PV panel to the AC grid voltage. From the three-stage configuration, the AC-DC converter at the first stage is eliminated. As a result, the PV panel output can be directly attached to the second stage of the three-stage configuration. The second stage is named Stage A. This stage is a DC-DC converter consisting of three parts, which are a DC-AC converter, an isolated high-frequency transformer, and an AC-DC converter. The high-frequency transformer is inserted into the DC-DC converter to provide voltage matching and galvanic isolation. Furthermore, the Stage A output is connected to a DC-AC converter, which is named Stage B. This converter is a Voltage Source Inverter (VSI). The VSI connects the Stage A output to the power grid. Hence, circuits in Stage A and Stage B deliver the electrical power from the PV panel to the grid and the load. Fig. 2 shows the implementation of the grid-connected PV system using SST.

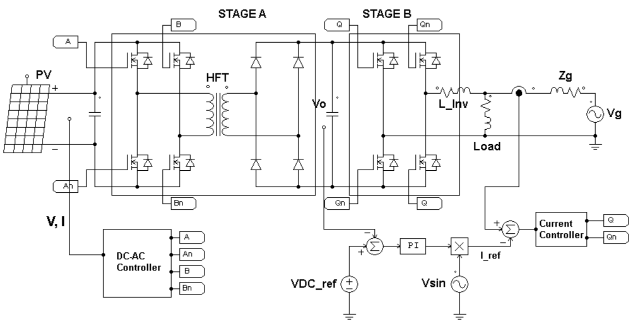

Fig. 2. Diagram of the on-grid PV system

A. Modified Solid State Transformer

The first part of Stage A is the DC-AC converter. The converter is used to convert the DC quantity from the PV panel output into the high-frequency AC quantity required by the high-frequency transformer operation. Its switching operation is also controlled to force the PV panel to produce maximum power. The converter consists of four transistors configured as a H-bridge. The left and right legs of the bridge each produce square waves with a duty ratio of 0.5. The square wave generated by each leg is phase-shifted by the displacement angle α. As a result, the output voltage of the bridge will be a three-level AC square wave (Fig. 3) with a pulse width of (180º – α). The PV maximum power can be achieved by adjusting the pulse width since the angle α determines the *rms* value of the square wave voltage as seen in Equation 1. The operating point (load lines) of the PV panel is associated with the *rms* value of the square wave voltage.

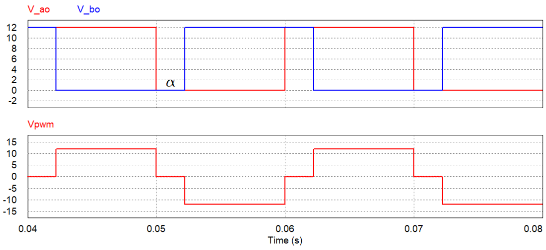

Fig. 3 Three-level square wave with a displacement angle α.

$$V_{sq-rms} = V_{dc}\sqrt{\frac{\pi-\alpha}{\pi}} \qquad (1)$$

The isolated high-frequency transformer as the second part of Stage A is a 5-kHz two-winding step-up transformer. The primary side is supplied from the DC-AC converter, and the secondary side is fed to the AC-DC converter. The transformer tries to match the PV panel output voltage level (≈ 35 V) to the VSI input voltage level (DC Bus voltage ≈ 350 V) by its winding ratio. The transformer also provides galvanic isolation between the PV panels and the grid.

For the last part, the AC-DC converter uses four diodes as a bridge and works as an uncontrolled rectifier. So, the number of system control circuits is reduced. The bridge receives a high-frequency AC voltage from the secondary side of the transformer and produces the DC bus voltage (V_o) which is the VSI input voltage on Stage B. The advantage of using the diode bridge is that it prevents power reversal to the PV panel because the power flow becomes unidirectional from the PV panels to the grid. There is a power capacitor installed at the DC bus as an energy storage to reduce the voltage ripple and to filter the AC component of the DC bus current.

B. Voltage Source Inverter

In Stage B, there is a grid-connected VSI. The VSI uses four transistors as a H-bridge. There is an inductor L_{inv} at the AC side of the VSI. It connects the output of Stage A to the single-phase power grid. Different from the previous DC-AC converter in Stage A, this VSI can be synchronized to the grid via a current controller.

The VSI has a current controller and a voltage controller [1][2]. The current controller senses the grid current using a current sensor. Then, the output signal of the sensor is compared to the sinusoidal reference current (i_{ref}), which is in phase with the grid voltage. By placing the current sensor on the grid side, the grid current is forced to be the same as the sinusoidal reference current (i_{ref}) which is given by:

$$i_{ref} = k\ v_{grid\text{-}1} \qquad (2)$$

where $v_{grid\text{-}1}$ is the fundamental component of the grid voltage, and k is the output of a PI controller. As a result, the VSI automatically provides the current (i_{inv}) according to:

$$i_{grid} = i_{inv} + i_{load} \qquad (3)$$

The grid current control will also regulate the flow of electrical power from the grid, the load, and the PV panel.

The voltage controller has a voltage sensor installed at the DC bus. The output signal of the sensor is compared to the DC bus reference voltage. Then, the error is regulated by a simple PI controller. The voltage controller tries to maintain the DC bus voltage constant at its reference value. The DC voltage reference value should be greater than the amplitude of the grid voltage wave. The voltage controller also defines the amplitude of i_{ref} by a gain k. This is an effective way of determining the required amplitude of grid active current since any active power mismatch among the grid, the load, and the VSI would result in the necessary corrections and regulate the DC bus voltage. The response speed of the voltage controller is much slower than that of the current controller. Hence, the current controller and the voltage controller are decoupled. Fig. 4 shows that the DC bus voltage (V_o) contains ripple but is constant at 350 V. Hence, the PI controller works correctly.

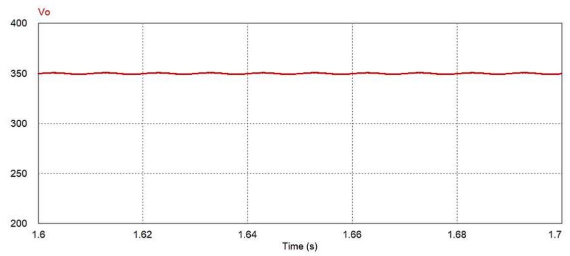

Fig. 4. DC Bus Voltage (V_o)

III. Simulation Results

To verify the concept, the circuit in Fig. 2 is simulated using PSIM simulator. The parameters used for the simulation are shown in Table I.

TABLE I. Circuit Parameters

Parameters	Value
Vg-rms	220 V
Z grid	0.02 Ω, 0.3 mH
L inv	0.25 Ω, 1.51 mH
Cap DC-bus	6600 μF
Transformer ratio	1: 13
$PV\ V_{mpp}$	35.6 V
$PV\ I_{mpp}$	28.1 A

A. PV Output Power

Fig. 5 shows the PV output voltage and current at its maximum power. To achieve the maximum power, the displacement angle (α) between the DC-AC converter legs must be 29°. The PV current, voltage, and power values are written in Table II. Fig. 6 demonstrates the voltage output of the DC-AC converter, which is a three-level square wave with a pulse width of 151°. V_{rms} = 32.74 V. The frequency of the wave is 5 kHz. This voltage is fed to the transformer primary winding. The transformer secondary voltage increases to 350 V (*rms*) due to its winding ratio. Its amplitude is held equal to the DC bus voltage.

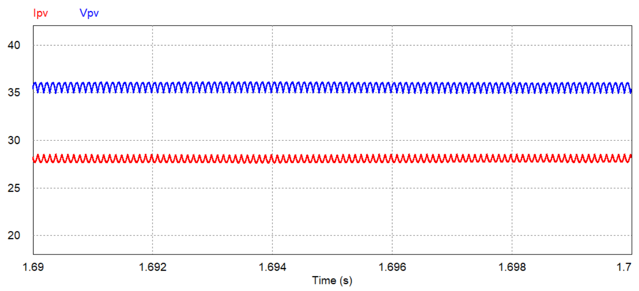

Fig. 5. PV output voltage and current for α = 29°.

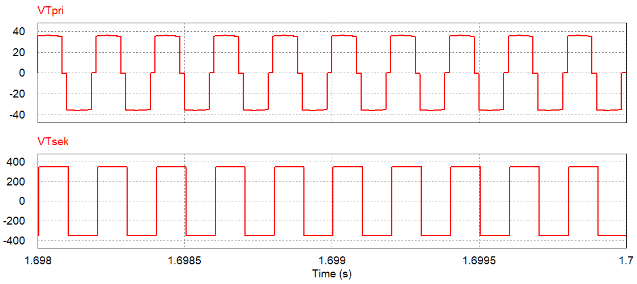

Fig. 6. Transformer primary (top) and secondary (bottom) voltage for α = 29°.

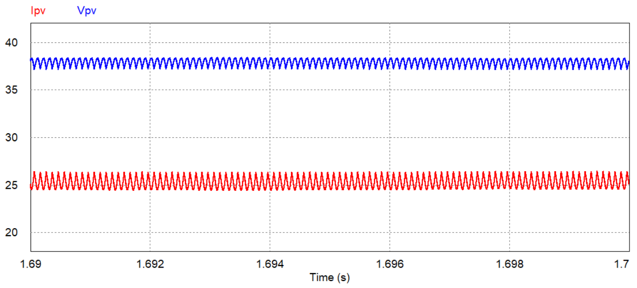

Fig. 7. PV output voltage and current for α = 60°.

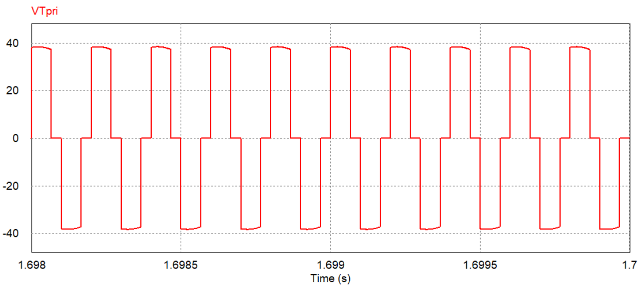

Fig. 8. Transformer primary voltage for α = 60°.

If the displacement angle is changed to 60°, then the PV output power is not maximum. Fig. 7 shows the PV output voltage and current. The current, voltage, and power values are written in Table II. The PV power is less than its maximum output power. The voltage output of the DC-AC converter, which is the same as the transformer primary voltage with a pulse width of 120° is shown in Fig. 8. V_{rms} = 31.14 V.

For a similar case with an angle of 10°, the PV output power is also not maximum. Fig. 9 displays the PV output voltage and current. The current, voltage, and power values are displayed in Table II. The PV power is also less than the PV maximum output power. The voltage output of the DC-AC converter, which is the same as the transformer primary voltage for α = 10° is shown in Fig. 10. V_{rms} = 34.29 V.

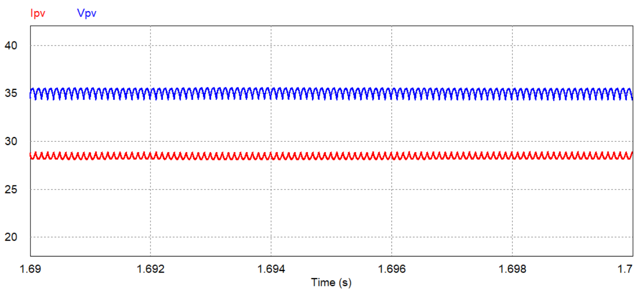

Fig. 9 PV output voltage and current for α = 10°.

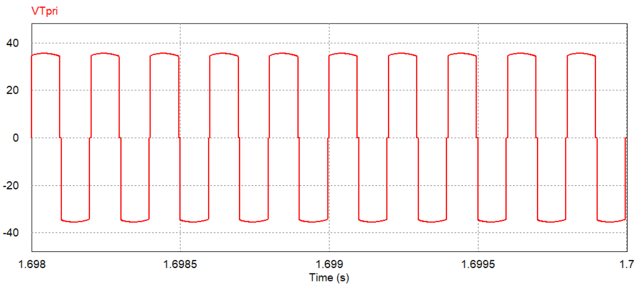

Fig. 10. Transformer primary voltage for α = 10°.

TABLE II. PV Panel Output

α	I_{pv} (A)	V_{pv} (V)	P_{pv} (W)
10°	28.41	35.12	997.76
29°	28.02	35.68	**999,81**
60°	25.31	37.92	959.41

It can be seen that the PV output power corresponds to the displacement angle of the DC-AC converter. The controller will adjust the converter switching time according to the angle. The angle defines the pulse width of the square wave, which determines the *rms* value of the DC-AC converter output voltage. Changing the angle will change the rms value of the voltage supplied to the high-frequency transformer. The transformer operates in variable voltage, which results in delivering variable power. The power passing through the transformer depends on the power available from the PV panel, which is determined by its load lines. Hence, the displacement angle is related to the operating point (load lines) of the PV panel.

B. Grid Currents

The load used in the simulation is linear and inductive (RL load). The observation is in steady-state conditions starting from t = 1.6s. Fig. 11 shows the grid voltage (top) and the grid, the load, and the VSI currents (bottom). In this case, α = 29°, and the PV panel works at maximum power. I_{inv} = 4.62 A, I_{load} = 2.91 A, and I_{grid} = 1.79 A.

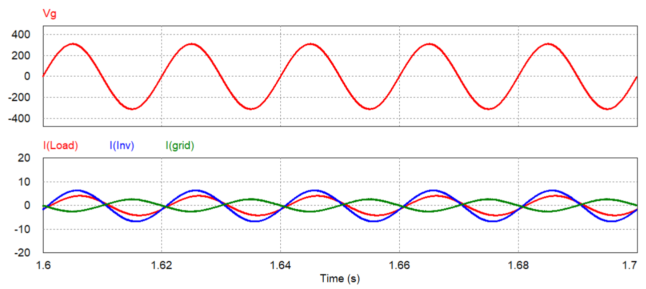

Fig. 11. The grid voltage (top) and the grid, the load, and the VSI currents (bottom) for $I_{inv} > I_{load}$

It can be seen that the inverter current is greater than the load current. It means that the PV panel generates more power than needed by the load. As a result, the excess power from the VSI is delivered to the grid. It is shown that the grid current is out of phase with the grid voltage. The direction of the grid current is from the VSI to the grid. The correlation of the grid current, the load current, and the VSI current agrees with Equation 3.

The grid current waveform is the same as the sinusoidal reference current (i_{ref}) due to the grid current controller. Zero crossings of the grid current are also the same as the grid voltage. Using the grid current controller, the VSI provides automatically reactive current so that the grid has a unity power factor.

The sinusoidal reference current (i_{ref}) is obtained from Equation 2. The PI controller output determines the reference current amplitude. Fig. 12 shows the PI controller output signal (k) (top) obtained from the voltage controller and i_{ref} (bottom) which is a multiplication of v_{grid-1} and k. The average value of k = – 2.51. As a result, the phase difference between the grid voltage and the grid current is 180°.

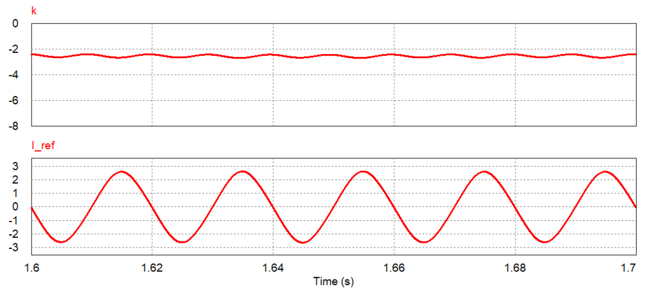

Fig. 12. The PI controller output signal and i_{ref} for $I_{inv} > I_{load}$.

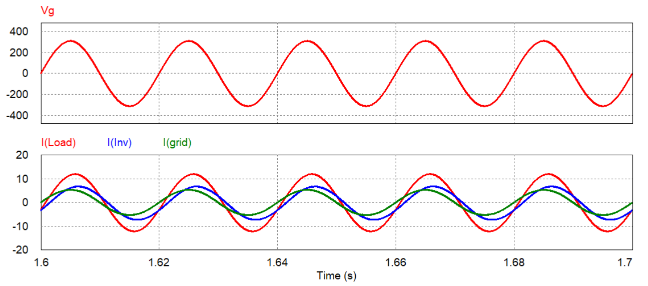

Fig. 13. The grid voltage (top) and the grid, the load, and the VSI currents (bottom) for $I_{inv} < I_{load}$

On the other hand, the inverter current is less than the load current. I_{inv} = 4.95 A, I_{load} = 8.53 A, and I_{grid} = 3.79 A. The PV panel output power is not sufficient for the load power consumption. Then, the deficit power to supply the load is drawn from the grid. Fig. 13 describes the grid current which is in phase with the grid voltage with a unity power factor. The direction of the grid current is from the grid to the load. The grid current cannot flow to the VSI because of the diode bridge rectifier. The correlation of the grid current, the load current, and the VSI current also agrees with Equation 3.

Fig. 14 shows the PI controller output signal, k (top) and i_{ref} (bottom). The average value of k = 5.37. Hence, any mismatch in the system power flow will change the value of k which adjusts the grid current amplitude. Because the value of k is positive, there is no phase difference between the grid voltage and the grid current.

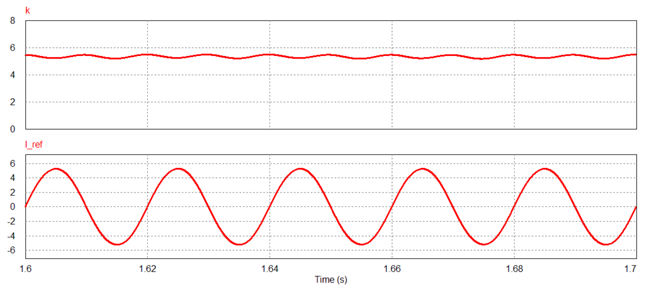

Fig. 14. The PI controller output signal and i_{ref} for $I_{inv} < I_{load}$.

The system can still work at night when the irradiance is very low. Fig. 15 shows the output voltage and current of the PV panel. There is no current flowing out from the PV panel. As a result, there is no electric power delivered through the SST and to the load/grid. The grid fully supplies the load power. However, the VSI still generates current to compensate for the load reactive current because the grid reference current (i_{ref}) is set to a unity power factor. Fig. 16 shows that the value of the grid current is similar to the load current but in phase with the grid voltage.

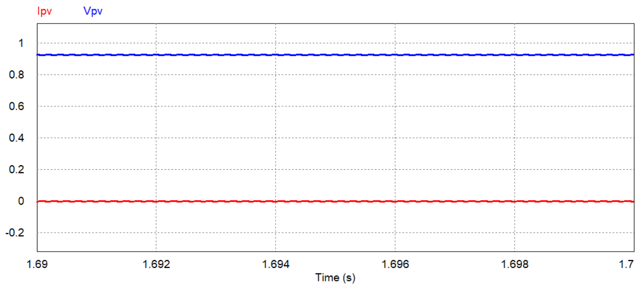

Fig. 15. PV output voltage and current for very low irradiance

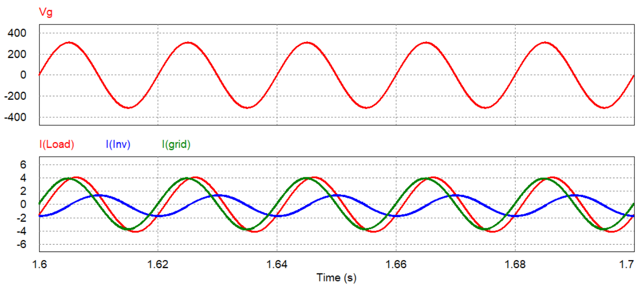

Fig. 16. The grid voltage (top) and the grid, the load, and the VSI currents (bottom) for very low irradiance.

IV. Conclusions

This paper explains a grid-connected PV system using a solid-state transformer (SST), which connects the PV panel to the grid. SST has been modified from three stages to two stages which is named Stage A and B. The modified SST consists of a DC-DC converter and a VSI. The DC-DC converter consists of a DC-AC converter, an isolated high-frequency transformer, and a simple bridge rectifier.

To send the solar energy to the load and grid, several conversion processes are carried out, starting from the DC quantity of the PV panel to the high-frequency three-level AC square wave for transformer operation. The transformer increases the voltage value. Then, the AC wave is converted to DC quantity again using a simple rectifier to supply the VSI. Finally, the VSI converts the DC quantity to a line frequency AC quantity and connects the system to the grid.

There are two control strategies. The first control strategy uses the pulse width of the square wave to determine the PV operating points (load lines). For the second control strategy, the VSI has a grid current controller and a DC bus voltage controller to regulate the flow of electrical power from the grid, the load, and the PV panel. All of the control strategies are decoupled so they can work independently.

Computer simulation results using PSIM prove that the SST system works very well. The PV power is delivered to the load and the grid through SST, while the grid current is sinusoidal and in phase with the grid voltage.

From the study above, this paper brings several contributions such as a modification of SST from an AC-AC converter to a DC-AC converter. It consists of the DC-DC converter and the VSI. The input voltage of the high-frequency transformer varies due to controlling the pulse width of the three-level square wave. The variable voltage affects the operating points of the PV panel. The power flow is unidirectional PV power and bidirectional grid power. The grid current is sinusoidal with a unity power factor.

Acknowledgment

The authors would like to thank PT. Bambang Djaja, Transformer Manufacturer, Indonesia for providing a high-frequency transformer.

References

[1] Tumbelaka, H.H., M. Miyatake, "Simple Integration of Three-phase Shunt Active Power Filter and Photovoltaic Generation System with Fibonacci-Search-Based MPPT," Proc. of IEEE Symposium on Industrial Electronics and Application (ISIEA), October 2010, Malaysia.

[2] Tumbelaka, H. H, and Borle, L. J., "Harmonic Mitigation Using a Polarized Ramp-time Current-Controlled Inverter," Telkomnika, vol. 8, no. 3. pp. 235-244, 2010.

[3] Tumbelaka, H. H., E. Muljadi, and W. Gao., "The Impact of Transformer Winding Connections of a Grid-Connected PV on Voltage Quality Improvement," International Journal of Renewable Energy Research, vol. 8, no. 1, pp. 7-14, March 2018.

[4] D. -Y. Jung, Y. -H. Ji, S. -H. Park, Y. -C. Jung and C. -Y. Won, "Interleaved Soft-Switching Boost Converter for Photovoltaic Power-Generation System," IEEE Transactions on Power Electronics, vol. 26, no. 4, pp. 1137-1145, April 2011

[5] Shadfar, H., M. G. Pashakolaei, A. A. Foroud, "Solid-state Transformers: An Overview of The Concept, Topology, and Its Applications in The Smart Grid," International Transactions on Electrical Energy System, vol. 31, no. 9, 2021.

[6] M. A. Hannan, et al., "State of the Art of Solid-State Transformers: Advanced Topologies, Implementation Issues, Recent Progress, and Improvements", IEEE Access, vol. 8, 2020.

[7] Sudhoff, S. D., W. Lafayette, "Solid State Transformer". US Patent No. 5,943,229, 1999.

[8] Saleh, S. A. M., et al., "Solid-State Transformers for Distribution Systems–Part I: Technology and Construction," IEEE Transactions on Industry Applications, vol. 55, no. 5, pp. 4524-4535, 2019.

[9] Silva, R. L. D., et al., "Solid-State Transformer for Power Distribution Grid Based on a Hybrid Switched-Capacitor LLC-SRC Converter: Analysis, Design, and Experimentation". IEEE Access, vol. 8, 2020.

[10] Madhu, K., Reddy, V. S. K., "Grid-Connected PV-Wind-Battery Based Multi-Input Transformer Coupled Bidirectional DC-DC Converter with Multilevel Inverter Fed AC Load," International Journal of Scientific Engineering and Technology Research, vol. 06, no. 32, pp. 6588-6593, November 2017.

[11] G. Brando, A. Dannier and R. Rizzo, "Power Electronic Transformer application to grid-connected photovoltaic systems," International Conference on Clean Electrical Power, Capri, Italy, pp. 685-690, 2009.