A NEW MODULAR THREE-PHASE INVERTER BASED ON SEPIC-CUK COMBINATION CONVERTER FOR PHOTOVOLTAIC APPLICATIONS

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Abstract

A new modular dc/ac inverter based on a dual-winding isolated SEPIC/Cuk converter for medium and high power Photovoltaic (PV) applications is introduced. In this system, several current-source submodules (SMs) are connected in series to allow for additional voltage boosting. Each SM is designed as a combination of SEPIC/CUK converter to offer a flexible output range and continuous currents with small ripple at input and output sides. Furthermore, the SMs structure can generate different output voltage polarities. The main purpose of employing small-size high-frequency transformers are to (1) provide galvanic isolation, (2) eliminate PV grounding problems, (3) achieve minimum electromagnetic interference (EMI). The paper presents a description of the proposed topology and investigate its reliability performance in a PV grid-tied system using MATLAB simulations. An experimental prototype has been used and controlled by TMS32028335 DSP, as a proof of concept.

1 Introduction

With the present high global energy consumption and industrial progress, fossil fuels are still considered as primary energy sources to meet the energy demand requirements. Consequently, climate change and green gas emissions have been existing global challenges. As the conventional energy sources (i.e. fossil fuels) have limitations of the product life cycle for the coming years, the global energy demands will be difficult to satisfy [1].

Alternatively, Renewable Energy Sources (RESs) are now considered for a weighty portion of energy generation and as a possible technology to solve the limited quantity of fossil fuels. Furthermore, RESs are anticipated to contribute significantly to future energy efficiency, security, and reduction in CO2 emissions [1].

Among all types of RES, the installed capacity of solar photovoltaic (PV) generators is witnessing the fastest growth and the total solar energy production was expected to exceed 500 GW in 2018. This rapid increase in the PV systems' capacity is spearheaded by European countries where PV capacity reached 103 GW in 2016. Therefore, the presence of photovoltaic systems (PV) becomes inevitable in the power generation area [2].

Traditionally, power converters for grid-connected photovoltaic systems (PV) particularly Medium and large-scale power systems face fundamental challenges. For example, it is required to install a bulky step-up transformer to meet the essential grid voltage boosting. The use of this transformer introduces high installation and maintenance costs in energy conversion systems [3,4]. Furthermore, it is known that the absence of isolation between the PV system and ground (as with the grid) is responsible for creating of common-mode voltages, which can cause leakage currents to flow through the PV system. Consequently, dangerous current levels may arise and hence affect the operation, safety and lifetime of a PV system negatively [5,6].

The significant progress of solid-state semiconductor devices in the last few decades has led to considerable improvement in grid-connected photovoltaic systems (PV). The modern power electronic topologies have developed to open a new horizon for enhancing switching efficiency, design optimisation and reducing the total power losses [7]. Therefore, the employed power inverters in PV applications should be able to offer bidirectional power flow and satisfying other requirements such as tracking the maximum power point as well as reducing the size, weight, and cost [8,9]. This will allow for mitigating PV system problems and for achieving efficient operations under various frequencies and weather conditions [10].

In this paper, a new modular inverter topology for grid-connected photovoltaic systems (PV) based on the dual-winding isolated SEPIC/Cuk converter is proposed. The inverter modular structure provides high-quality output voltages and currents into the grid without using large transformer components. Furthermore, it improves system's reliability, especially during dc and ac faults. If some submodules are faulted for any unexpected reason, they can be by passed or replaced with redundant submodules.

The most interesting feature in the inverter structure is its ability for employing high-frequency transformers which can offer the required galvanic isolation. The presence of the isolation is important for solving the grounding issues of the PV panels and improve the safety concerns of the system. Moreover, with increasing the operating frequency of the inverter, the sizes of these isolation transformers can be reduced significantly.

Because the employed submodules are based on the SEPIC-Cuk converters, the proposed inverter has the advantage of providing smooth continuous input currents that are desirable for the MPPT controller operational. Thus, recourse to plastic or film capacitor filtering instead of employing a bulky electrolytic capacitor, which is the main source of unreliability in the PV system.

The rest of this paper gives a detailed description of the proposed inverter system in section 2, along with the modulation technique which will be discussed in section 3. Then, the principle of operation of this system will be presented in section 4. The inverter system has been evaluated with simulations, using MATLAB/Simulink and the results are described. Finally, a scaled-down prototype is developed and controlled with TMS32028335 DSP.

2. SYSTEM DESCRIPTION

Fig.1 shows a novel architecture of the three-phase modular structure which is formed by the series connection of submodules (SMs) consisting of isolated SEPIC/Cuk converters. Each SM has an identical front structure and two output terminals that are beneficial for performing efficient power conversion by providing dual output voltages. The unique feature here is that the gate signal is the same for the output switches S_{aN} and S_{bN}. Therefore, their output voltages have equal magnitude, but opposite polarity. Where the output voltage is positive for the upper terminal (SEPIC output) and negative for the lower terminal (Cuk output).

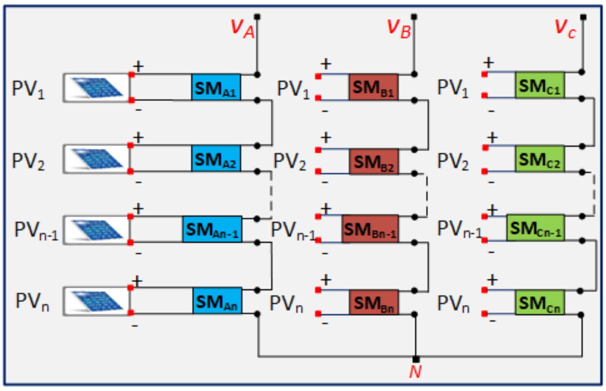


Figure 1 Block diagram of proposed system

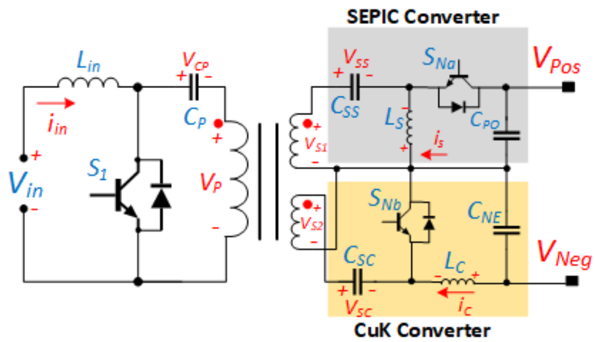


Figure 2 The employed SM

3 Modulation technique

To operate the SEPIC/CUK converter, the duty cycle ratio (D) is compared with a saw-tooth carrier signal to generate the PWM signals for the converter's switches. Fig.3 shows the output voltage waveforms of two successive submodules (SMs). Each SM generates a sinusoidal ac voltage plus a dc voltage component. The resultant voltage of the two successive SMs is shown in Fig. 3 as ac voltage at the grid frequency. Each converter SM can be connected individually to a PV module it can be clustered with other SM in parallel with the PV module.

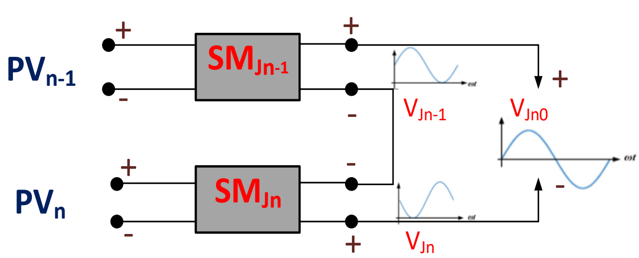


Figure 3 Modulation scheme

Where J the phases (a, b or c) and n presented number of the modules. Thus, the output voltage for each SM can be delivered as follows.

$$V_{Jn-1} = \frac{1}{2} V_{n-1} \sin \omega t + V_{dc\,n-1}$$

$$V_{Jn} = \frac{1}{2} V_n \sin(\omega t + \pi) + V_{dc\,n}$$

$$V_{JnO} = \frac{1}{2} V_{n-1} \sin \omega t + V_{dc\,n-1} - \frac{1}{2} V_n \sin(\omega t + \pi) - V_{dc\,n}$$

Since both V_{Jn-1} and V_{Jn} are equalled alongside $V_{dc\,n-1} = V_{dc\,n}$ consequently the out voltage is;

$$V_{JnO} = V_n \sin \omega t$$

4 Modes of operation

The circuit topology is consisting of three switches and diodes. The complementary switching singles of S_1 and S_N control the output voltage of the circuit. Both switches S_{aN} and S_{bN} are turned on and off at the same time. Without losing the generality, explaining the operation can be conducted for non-isolated version in continuous conduction mode (CCM). Thus, system operation is associated with the states of S_1 and S_N switches which can be divided into two operating modes.

Mode 1:

The switch S_1 turned on and the S_N is off, the flowing current paths are shown in Fig.4. In this mode, the input inductor is charged by its current I_{in} and both SEPIC and Cuk capacitors are connected to ground by the switch S_1. Hence, L_s is energised by the current I_s. Meanwhile, the SEPIC capacitor C_s is discharging and its energy is transferred L_s. While the Cuk inductor is charging because the voltage magnitude of input side is greater than outside causes Cuk capacitor to release its energy stored into Cuk inductor.

Mode 2:

As shown in Fig.5 during S_N is on and S_1 is off, the inductor L_{in} transfers its energy to the capacitors C_s and C_c. Therefore, the input current I_{in} decreases. Meanwhile, the output inductors L_s and L_c also transfer their energies to C_p and C_N respectively and the magnitude of I_s and I_c decrease.

5 Simulation results

The inverter system has been built and investigated in open loop operation. The system is simulated using MATLAB/Simulink to study the inverter performance in detail. The model has four SMs per phase and its parameters are given in Table 1.

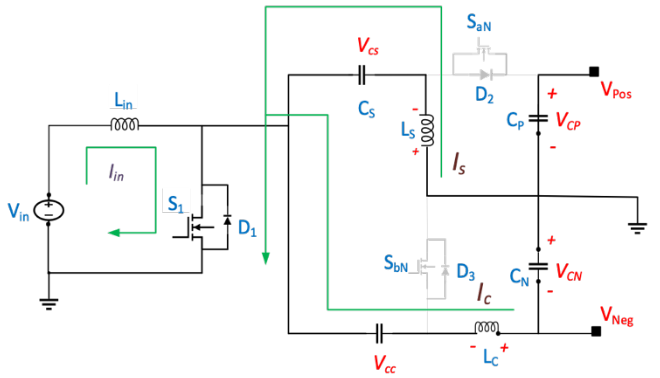


Figure 4 Mode 1

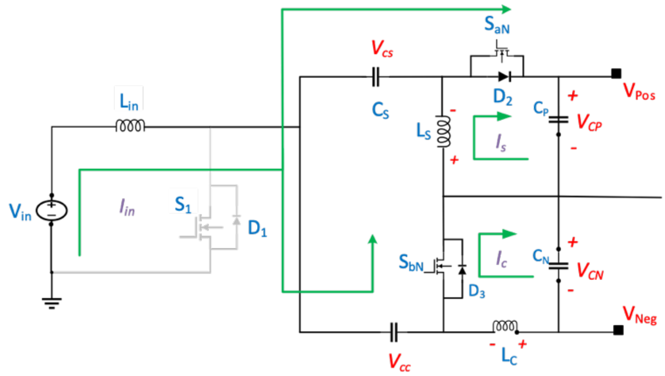


Figure 5 Mode 2

Parameters	Value
(SMs) per phase	4
DC input voltage (V_{in})	100 V
Switching frequency (f_{sw})	50 K Hz
fundamental frequency	50 Hz
Output Resistor (R)	30 Ω
ALL Capacitors (C)	10 µF
ALL inductors (L)	10 mH

Table 1

The three-phase output voltage and currents are shown in Fig. 6 and Fig. 7 while the input DC current of the first PV module is shown in Fig. 8. Each SM generates two output voltages with opposite polarities, from a single input PV voltage as it is shown in Fig9.

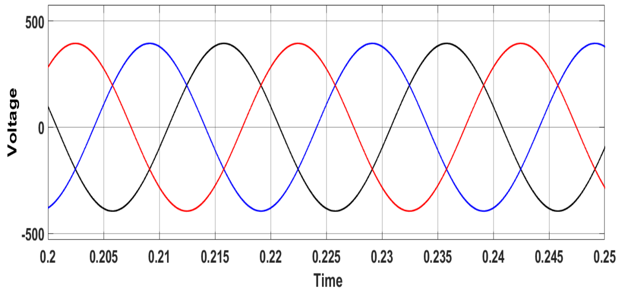


Figure 6 Three-phase voltages

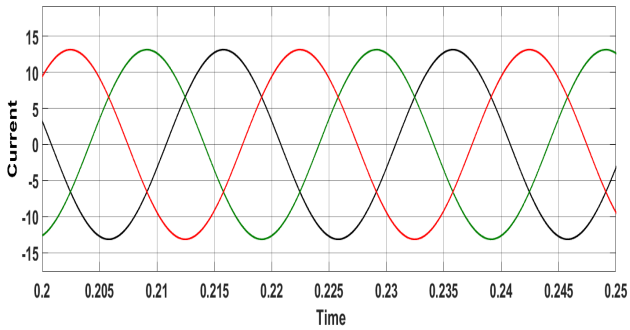


Figure 7 Three-phase currents

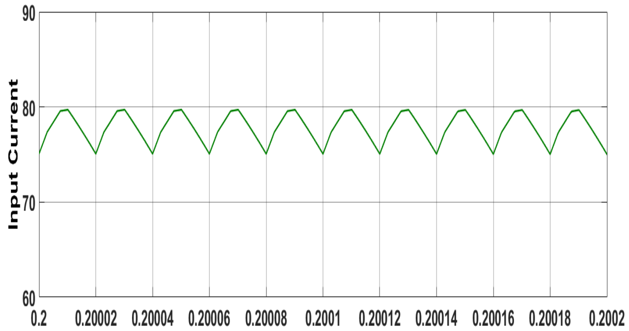


Figure 8 Input DC current

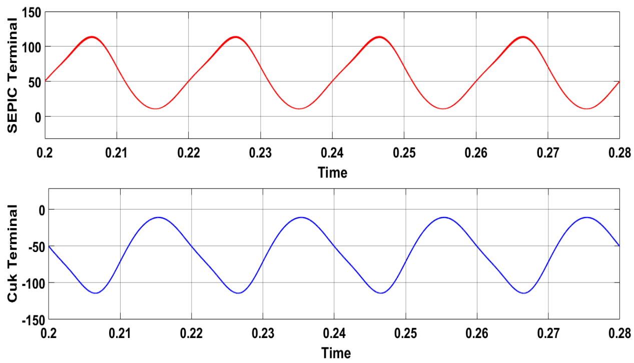


Figure 9 SM1 voltages

6 Experimental validation

Fig. 10 shows the experimental setup used in this work. The system is controlled by TMS32028335 DSP and uses the parameters in Table 2. Each SM will deliver 250W and hence the total power is 3 kW. The input voltages of the modules are controlled by an external power supplies to mimic the PV modules.

Parameters	Value
(SMs) per phase	4
DC input voltage (V_{in})	200 V
switching Frequency (F_c)	50 K Hz
fundamental frequency	50 Hz
Output Resistor (R)	22 Ω
ALL Capacitors (C)	30 µF
ALL inductors (L)	11 mH
Semiconductor switches	IRG4PC50FPbF
Diodes	FFSH40120ADN

Table 2

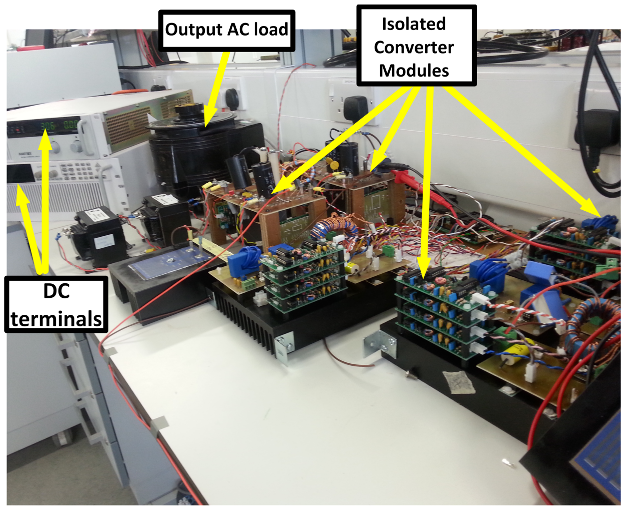
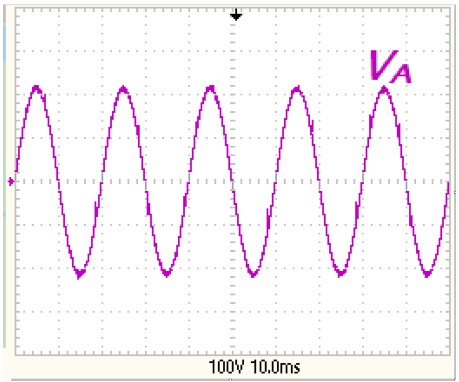
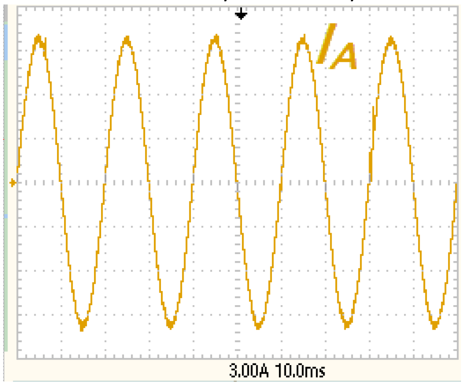


Figure 10 Experimental setup

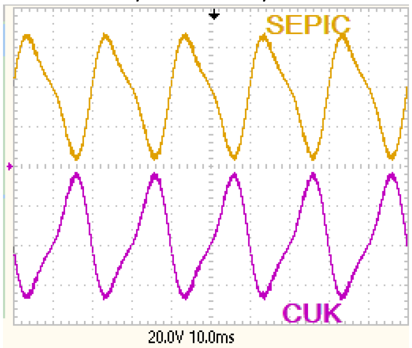
Fig. 11 shows the three-phase operation results when the system is generating 3 kW across the three 22 Ω loads. Fig. 11a shows the phase a and Fig. 11b shows phase a current. The dual voltages of SMs in module 1 are shown in Fig. 11c. Fig. 11d shows the total input current of the 12 SMs together. To check the capability of the system in grid-connected mode, 1 phase is connected to the single-phase grid using a single-phase AC transformer and the voltage of common coupling is kept at 200V (peak). Fig. 12 shows the ac output voltage, ac output current, SM1 output voltages and the total input current from the DC supply.



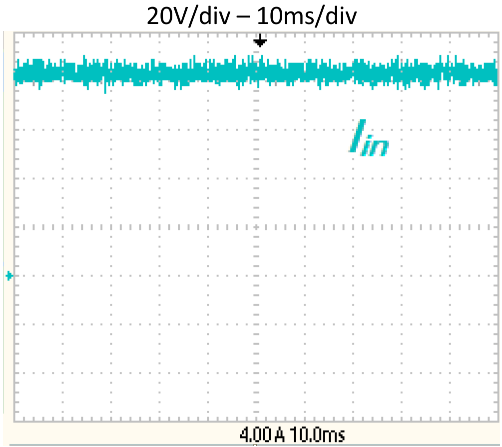
(a) Phase 1 voltage
100V/div – 10ms/div



(b) Phase 1 current
3A/div – 10ms/div

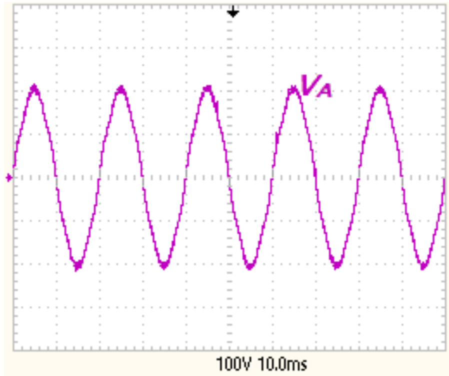


(c) SM1 voltages
20V/div – 10ms/div

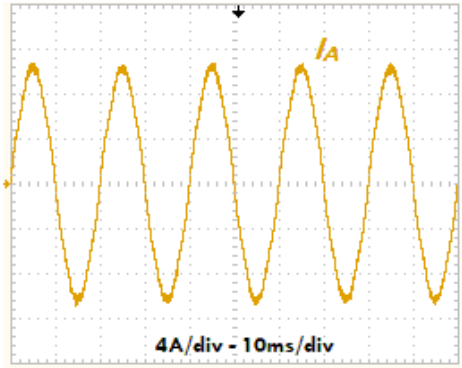


(d) Input DC current
4A/div – 10ms/div

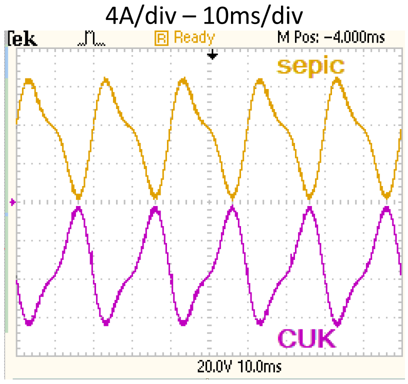
Figure 11 Three-phase operation



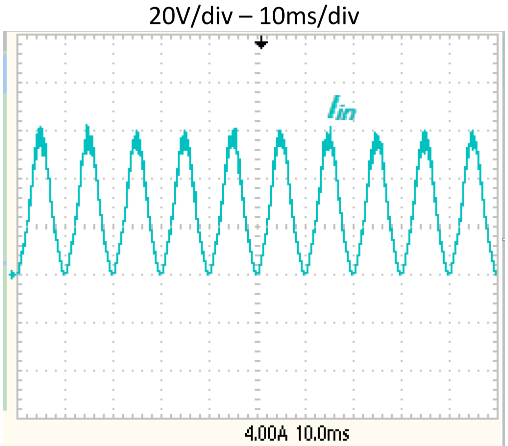
(a) Phase 1 voltage
100V/div – 10ms/div



(b) Phase 1 current
4A/div – 10ms/div



(c) SM1 voltages
20V/div – 10ms/div



(d) Input DC current
4A/div – 10ms/div

Figure 12 Single-phase operation

7 Conclusion

The paper presents a new three-phase modular series-connected system for medium-voltage PV applications. The proposed inverter has attractive features that nominate it as a modern generation power inverter for large-scale PV system. This fact comes from its ability to: (i) operate as a current sourced converter with continuous input current, (ii) enable bidirectional power flow and galvanic isolation versions, (iii) provide a high level of modularity and scalability, and (iv) offer a flexible output voltage range which is necessary for the control schemes. Eventually, a control design strategy and an appropriate (Maximum Power Point Tracking) MPPT system will be presented in future publications.

8 Acknowledgements

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9 References

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