GaN DC/AC Multilevel Converter for PV Application

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Abstract—**The thesis deals with the design of a three-level flying capacitor inverter for the photovoltaic application connected to the American electricity grid based on the last generation of GaN FET devices. Several electrical and thermal simulations are carried out to investigate the flying capacitor converter operation. The thesis explores the devices power losses, thermal management, flying and dc-link capacitors voltage ripple and output current ripple waveforms with the target of implementing an accurate converter design approach. Finally, it covers the full converter electrical schematic of the converter topology for both the power stage, the driver and the sensor circuits.**

I. Introduction

In renewable energy conversion, smart grid arrangement, energy storage management, and sustainable transport systems, the multilevel converter topologies are attractive solutions to increase input voltage, improve output waveform quality and reduce harmonic content. Wide bandgap (WBG) switching devices for converter applications have emerged to address these sustainable development challenges in recent years. Among the WBG devices currently on the market, high electron mobility gallium nitride (GaN) transistors (HEMTs) offer significant advantages and prospective over existing Silicon-based and Silicon-Carbide (SiC) MOSFETs. In the thesis, a flying capacitor inverter based on a GaN FETs is explored. The electrical and thermal design of the single phase 3-L flying capacitor converter using PLECS and LT-Spice environments have been done. The input voltage on the inverter dc-bus (V_{dc}) is fixed to 400 V. The PV panel is connected to a flying capacitor converter via a boost converter to obtain a DC voltage of 400 V (Fig.1). In this work, only the inverter side will be considered. The flying capacitor converter output voltage (V_{out}) chosen is the American grid voltage of about 110 V_{RMS} with a peak value of 155 V and frequency of 60 Hz. An output current of 15 A and a system power of 1 kW are fixed as design target. The converter design approach is done, and a complete electrical schematic is achieved. The thesis is developed with strictly at one of the leading international companies designing and developing GaN FET devices. The thesis work activity was conducted at the Efficient Power Conversion Corporation (EPC) Centre of Excellence on motor control applications with GaN FET devices in Volpiano (Torino).

II. GaN Transistors

GaN power devices are high electron-mobility transistors (HEMTs) belonging to the wide-bandgap materials (WBG). GaN devices presents higher breakdown strength, faster switching speed, higher thermal conductivity and lower on-resistance with respect to silicon-based devices. A normally off GaN FET is based on an enhanced structure (e-mode). The GaN FETs which will be used in this thesis work are e-mode GaN power transistors from EPC.

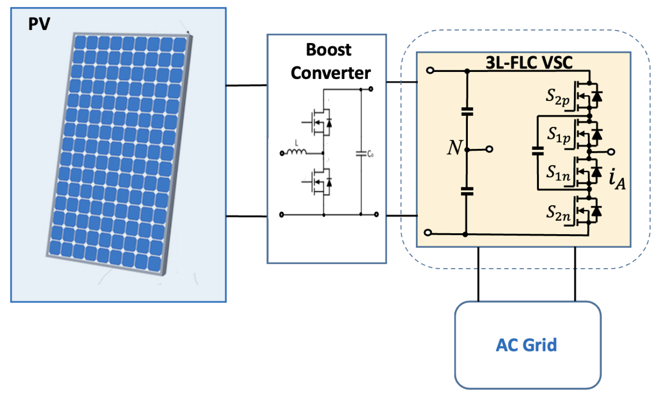

Fig. 1. Overall application system block model.

III. Multilevel Topologies

The multilevel converters (MC) are an evolution of the two-level converter concept. The multilevel converter output is a step-stepped waveform voltage, which depends on the converter levels. The MC are useful to reduce Total Harmonic Distortion (THD), emulating a sinusoidal waveform better than two level converters. Several power converter topologies belonging to the multilevel converter circuits are investigated. Finally, the flying capacitor 3-L converter (Fig.1) has been chosen for the following reasons:

- The voltage stress of switches is equal to half dc-bus total voltage. This allows to use the chosen GaN transistors;
- The modularity of this topology permits to add new cells to have more voltage levels;
- The topology presents a two carriers modulation technique;
- The topology permits to consider this application on microinverter with single PV voltage supply.

IV. Application design and simulations

The electrical and thermal design of the single phase 3-L flying capacitor converter using PLECS and LT-Spice environments have been discussed. The converter investigation addresses the following points:

- GaN transistor selection;
- Modulation technique of the three level Flying Capacitor converter;
- Power Losses Analysis;
- Thermal Analysis;
- Flying Capacitor design.

A. *GaN transistor*

The transistor selected for the 3-L Flying Capacitor converter is the EPC2050. The EPC2050 is an enhancement mode GaN transistor from EPC with $R_{DS,on}$ typically equal to 55 $m\Omega$; the maximum drain-source voltage is 350 V.

B. *Modulation Technique*

To achieve a multilevel output voltage, the cells must use individual carriers phase shifted by $2\pi/m$ as an interleaving approach. This modulation technique obtains a frequency multiplication effect in output waveforms.

C. *Power Losses Analysis*

LT-Spice is used to analyse the circuit and switches operation of the multilevel converter. Simulation results investigate the power losses of the devices (switching cells). In this section, the switching losses and the losses in the case of direct and reverse conduction are evaluated, with several dc input voltage and output currents, and considering different working temperatures at 100 kHz. The parallel connection overall losses for high-current switches are also investigated. Two paralleled GaN FETs are selected to trade-off between the power losses and the requested current.

D. *Thermal Analysis*

A tool called GaN Power Bench from EPC was used to design the thermal circuit of the multilevel inverter. This thermal calculator provides quick estimates for the thermal performance parameters of PCB-mounted GaN devices subject to both board-side cooling through forced convection and backside cooling through a thermal solution consisting of a heat spreader and heatsink. The thermal circuit model in the PLECS simulator is implemented to investigate the thermal operative conditions. The switching frequency of the inverter is related to two parameters: efficiency and thermal management of the system. From several simulation runs, the frequency to maximize the efficiency is 100 kHz (Fig.2) at the maximum current imposed (15 A).

E. *Flying Capacitor design*

Assuming a voltage ripple of 5% of the voltage applied across the flying capacitor (200 V), the capacitance value is related to the voltage ripple requested. The voltage ripple of the flying capacitor has a particular characteristic. It increases as the modulation index decreases. The capacitance value considered for the converter at an output current of 15 A and 60 Hz of the output frequency is 2.68 μF at 90% of the output voltage.

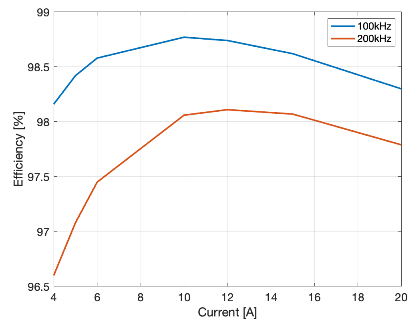

Fig. 2. Efficiency map with two switching frequency values depending on output current of the system.

V. Flying Capacitor Converter Schematic Design

The various components useful for the flying capacitor 3-L inverter design is considered to achieve a complete schematic of the power stage (Switching cell), a driver circuit, the dc Link and flying capacitors, sensors circuits to monitoring capacitors voltages and output current, output and input conditioning circuits and several requested power supply circuits. The schematic is developed in the Altium software environment. The power stage of a switching cell with a driver circuit is depicted in Fig.3.

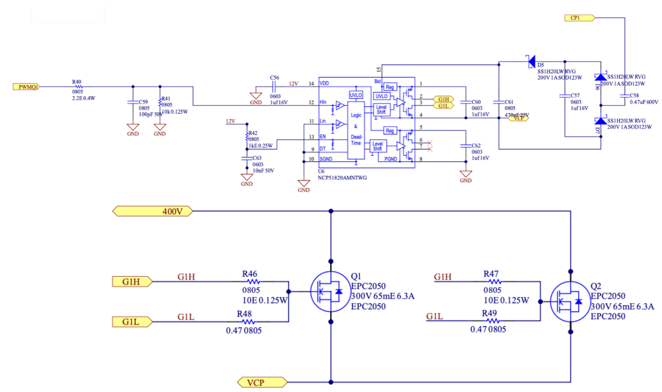

Fig. 3. Power stage of a switching cell with driver circuit schematics.

VI. Conclusions

The thesis involved designing and engineering a flying capacitor three levels GaN-based inverter for photovoltaic applications. The inverter described is the last stage between the solar panel and the grid connection. The inverter is designed to provide an output voltage equal to the American grid voltage of 110 V_{RMS} and with a frequency of 60 Hz. Through simulations using the LT-Spice and PLECS software, the system is investigated. It can reach an output power slightly higher than 1 kW with a maximum output current of 15 A. The last generation of WBG GaN FETs characteristics permits an increase in the converter's switching frequency with an increase in system efficiency with consequent size reduction. The inverter GaN FET devices feature low switching and reduced conduction losses. The inverter topology has been designed using two devices in parallel for each power cell.