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International Conference on Components and Systems for DC Grids
14 - 15 March 2017, Grenoble, France

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Abstract

Today, photovoltaic (PV) plants operate at low DC voltage (maximum 1.5 kV) and inject power in the low-voltage, single-phase or three-phase public grid via an inverter. In PV plant from some hundreds of kilowatt, power is injected in the medium-voltage three-phase public grid using transformer between the inverter and the grid. PV plants of hundreds of megawatts are today in operations and silicon-carbide (SiC) power semiconductors with high breaking voltage capabilities are available on the market or under samples, allowing to design static converter with higher efficiency than IGBT based ones. This leads to consider the development of DC-side medium-voltage PV plant for high power applications. An 18 kW, 3 kV PV string is built to demonstrate the feasibility of such a medium-voltage PV plant.

Keywords

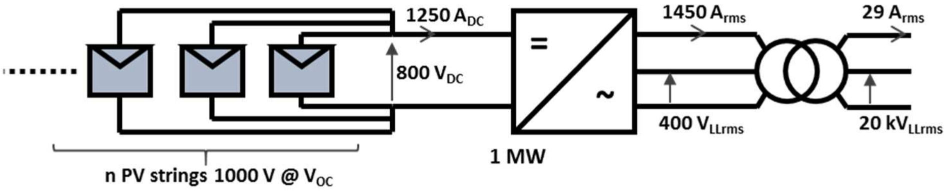
PV Module, PV Plant, Medium-Voltage, Static Converter, Inverter, Power Semiconductor, Silicon Carbide, Contactor, Disconnector, Buck Chopper

I. Introduction

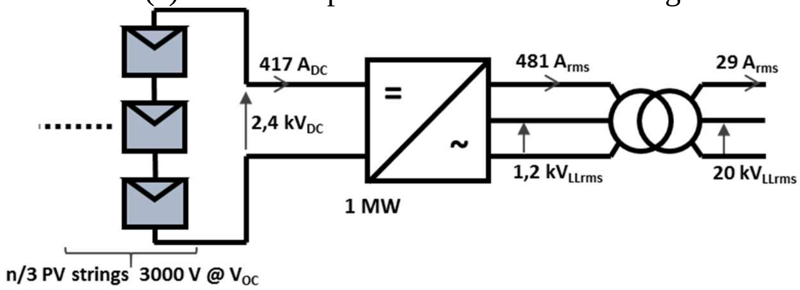
Most of the PV plants currently in service in the world, work under DC low-voltage at a maximum of 600 V or 1 kV in open-circuit. Electrical power is injected using inverters in the single-phase 230 V_{RMS} public grid (in residential application, some kilowatts) or in the three-phase 400 V_{RMS} or 690 V_{RMS} grid up to some hundreds of kilowatts. In higher power PV plants, transformers are added in order to inject power in the three-phase 20 kV_{RMS} medium-voltage grid. The current trend is the increasing of the PV strings DC voltage to 1.5 kV in open-circuit for high power plants in order to decrease the DC cables cost by reducing their number. The maximum DC voltage of the PV plants is 1.5 kV as it is the limit of the low-voltage domain; higher voltage imposes to consider the most stringent standards of the high-voltage domain.

Today, PV plants of hundreds of megawatts, up to 1 gigawatt, are installed in the world [1] injecting power in high-voltage AC grids. Simultaneously, silicon-carbide (SiC) power semiconductors of 1.2 kV and 1.7 kV blocking-voltage are on the market [2] followed by 3.3 kV and 10 kV available samples [3] allowing important improvements of high-voltage static converters which are now using silicon 6.5 kV IGBT or IGCT. These technological innovations allow to consider high-voltage high-efficiency static power converters for use in PV application.

Figure 1 shows a schematic comparison of two 1 MW PV plants connected to the 20 kV_{RMS} three-phase grid; the first composed of traditional 1 kV PV strings, and the second composed of 3 kV PV strings using PV modules with the same electrical characteristics.



(a) 1 MW PV plant with n 1 kV PV strings



(b) 1 MW PV plant with n/3 3 kV PV strings

Figure 1 – Schematics comparison of a 1 kV and a 3 kV, 1 MW PV plants

To prove the technical feasibility of medium DC voltage PV plants, The CEA is building, in the French National Institute for Solar Energy (INES) site, an 18 kW demonstration PV string working at 3 kV.

As other electric system, PV plants need equipment like contactor and disconnector for safety. Such equipment, when used in medium DC voltage application, are available on the market for railways application. As the maximum typical DC voltage in railway traction is 3 kV, this voltage level is chosen for the demonstrator in order to find available equipment.

The current demonstrator is composed of the 3 following main elements:

- Special insulated PV modules
- PV plant
- Medium-voltage static DC/DC converter for power injection on resistive load

This paper presents the current results of the installation of this 3 kV medium-voltage PV plant.

II. Special reinforced insulation PV modules

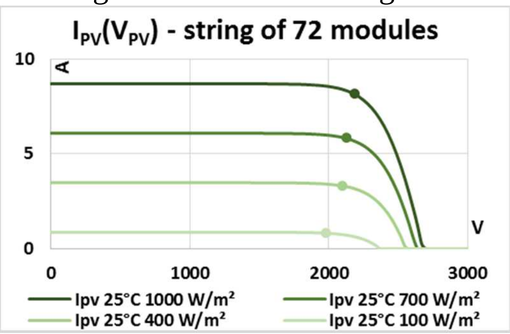
The 3 kV PV string is obtained by serial connecting PV modules, 3 times more modules than a 1 kV traditional PV string. Special 3 kV reinforced insulation PV modules must be used because, according to the conversion stage topology, this maximum voltage can be applied between the positive and negative poles of the strings and the earth, knowing that PV modules frames are connected to the earth.
Special PV modules have been built at INES for the demonstrator for working in 3 kV PV strings. Electrical characteristics of a single PV module in STC condition (1000 W/m² solar irradiation and working temperature of 25°C) are listed Table I.

72 of these modules, serial connected are used to build the 3 kV (in open-circuit) string. This maximum voltage is obtained when the plant work in the minimal temperature conditions (-20 °C is considered)

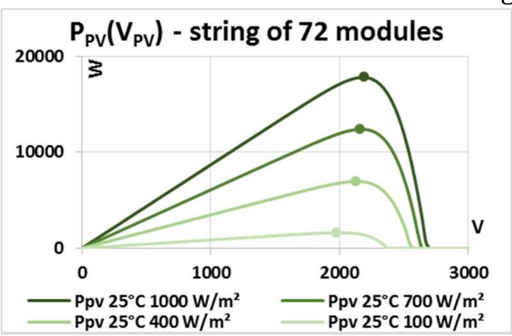
TABLE I – PV MODULES CHARACTERISTICS AT STC (1000 W/M²; 25 °C)

Symbol	Parameter	Value
N_{cell}	Number of PV cells	60
P_{MPP}	Power at maximum power point	250 W
V_{MPP}	Voltage at maximum power point	30.5 V
I_{MPP}	Current at maximum power point	8.2 A
V_{OC}	Open-circuit voltage	37.6 V
I_{SC}	Short-circuit current	8.7 A
S_{module}	Module surface	1.65 m²
η_{module}	Module efficiency	15.1 %

From the characteristics of a single PV module, the $I_{PV}(V_{PV})$ and $P_{PV}(V_{PV})$ curves of a 72 serial modules string can be obtained using a simulation software. These curves are shown Figure 2.



(a) $I_{PV}(V_{PV})$ curves



(b) $P_{PV}(V_{PV})$ curves

Figure 2 - $I_{PV}(V_{PV})$ and $P_{PV}(V_{PV})$ characteristics of a 72 PV modules string

The insulation resistance of these special modules must be measured in order to comply with the PV modules standard [4, 5].
According to the class B standard requirement, 4 times the maximum working voltage plus 2 kV must be applied between the poles and the earth (14 kV in our case) and the leakage current measured. The insulation resistor multiplied by the surface module is then calculated and must be superior or equal to 40 MΩ.m². The insulation resistance measured on the INES special modules is about 4000 MΩ.m².

III. The 18 kW, 3 kV PV plant

The PV plant demonstrator is implemented on the INES rooftop by using 72 special modules in series and specific devices such as DC high-voltage contactors, disconnectors, connectors and cables for insuring the security of staff working on this type of plant.
A general schematic of the installation composed of the PV string, the DC/DC static converter and the resistive load is illustrated Figure 3.

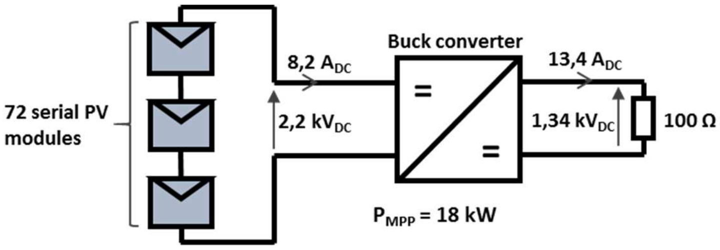


Figure 3 – General schematic of the demonstration PV plant

The 72 PV modules are arranged on two parallels frame as shown on Figure 4. DC medium-voltage equipment is installed on the related prefab.

Figure 4 – General view of the PV plant on INES rooftop

The installed PV connectors and cables are market available device intended for 1.5 kV traditional PV plant. These connectors and cables have been tested to check there insulation resistance at 14 kV in the same way as for the PV modules. The resistance measured on a cable + connector sample is about 200 GΩ

Disconnectors and contactors of Figure 5 have been selected in order to operate at 3 kV DC/ 10 A DC minimum and, for the contactor, to be able to interrupt a DC current less than 10 A. These devices are serial connected with the PV string to interrupt the current and disconnect the plant when needed.

(a) 5 poles rotary switch for disconnexion (b) DC contactor for current interrupting

Figure 5 – equipment chosen for the disconnector and the contactor

IV. Static converter

In this demonstrator, as the goal is to validate the working of the PV string and operate it at its maximum power point (MPP). A DC/DC converter (buck chopper) is used. The power is dissipated in a resistor. In a future step, this converter will be replaced by an inverter followed by a transformer in order to inject power in the three-phase grid.

1. Electrical sizing

The electrical schematic of the buck chopper considered topology is given Figure 6.

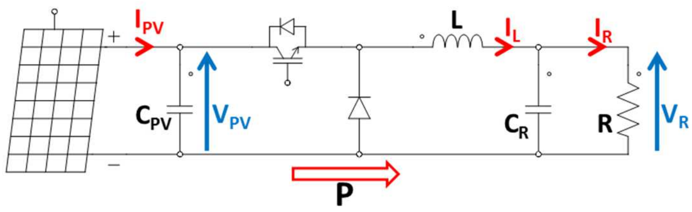


Figure 6 – Schematic of the buck chopper

The electrical characteristics of this conversion stage are listed Table II.
The inductor value L is calculated using equation (1) as function of the desired current ripple; the PV-side capacitor value C_{PV} is calculated using (2) and load-side capacitor value C_R with (3), these capacitors must be sized in order to limit the PV and load voltage ripple respectively.

TABLE II – BUCK CHOPPER ELECTRICAL CHARACTERISTICS

Symbol	Parameter	Value
P	Power	18 kW
V_{PV}	PV nominal voltage	2.2 kV
I_{PV}	PV nominal current	8.2 A
R	Load resistance	100 Ω
V_R	Load voltage	1.34 kV
I_R	Load current	13.4 A
α	Chopper duty ratio	0.61
ΔI_L	Inductor current ripple	40% I_L
ΔV_{PV}	PV voltage ripple	1% V_{PV}
ΔV_R	Load voltage ripple	1% V_R
f_{SW}	Switching frequency	2 kHz
L	Inductor value	50 mH
C_{PV}	PV-side capacitor value	75 µF
C_R	Load-side capacitor value	25 µF

$$\boldsymbol{L = \frac{V_R \times (1-\alpha)T_{SW}}{\Delta I_I}} \quad (1)$$

$$\boldsymbol{C_{PV} = \frac{I_{PV} \times (1-\alpha)T_{SW}}{\Delta V_{PV}}} \quad (2)$$

$$\boldsymbol{C_R = \frac{\Delta I_L \times T_{SW}}{8 \times \Delta V_R}} \quad (3)$$

2. Thermal sizing

The IGBT and diode needed are packaged in a single power module [6], the breaking voltage is 6.5 kV and the nominal current is 250 A (as there is no available power module with smaller current rating).

From the power module datasheet, power losses, temperature in operation and the corresponding maximum thermal resistance of the heatsink can be calculated. Thermal sizing parameter are listed Table III. The thermal resistance of the heatsink must be inferior to 0.04 K/kW so a fan should be added.

TABLE III – BUCK CHOPPER THERMAL CHARACTERISTICS

Symbol	Parameter	Value
P_{cond_IGBT}	IGBT conduction losses	10 W
P_{cond_diode}	Diode conduction losses	5 W
P_{SWon_IGBT}	IGBT turn-on losses	370 W
P_{SWoff_IGBT}	IGBT turn-off losses	120 W
P_{SWoff_diode}	Diode turn-off losses	315 W
$P_{LOSSEStot}$	Total losses	820 W
R_{JC_IGBT}	Junction-to-case IGBT thermal resistance	26.1 K/kW
R_{CH_IGBT}	Case-to-heatsink IGBT thermal resistance	26.5 K/kW
R_{JC_diode}	Junction-to-case diode thermal resistance	56 K/kW
R_{CH_diode}	Case-to-heatsink diode thermal resistance	42 K/kW
R_{grease}	Grease thermal resistance	15 K/kW
T_{J_IGBT}	Considered IGBT junction temperature	125 °C
T_{J_diode}	Considered diode junction temperature	125 °C
T_A	Considered ambient temperature	60 °C
R_{HA}	Heatsink needed thermal resistance (forced air)	≤ 0.04 K/kW

4. Mechanical sizing

Figure 7 is a 3D view of the chopper power stack under construction. 100 µF, 1.2 kV capacitors have been chosen so a 4 levels busbar must be designed.

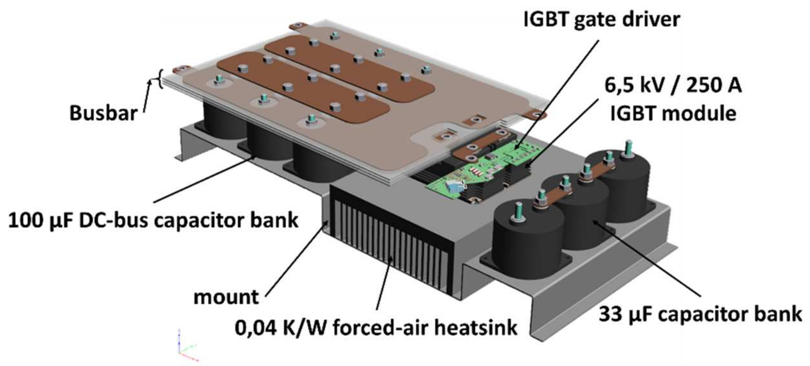


Figure 7 – 3D view of the buck chopper power stack (without inductor,cooling fan and control board)

V. Perspectives

1. Measurements

Once the whole system will be in operation, measurements must be done to validate - or not – the working of the medium-voltage PV plant. These measurment are :

- Earth leakage current, as there are parasitic capacitors between the PV modules poles and the earth. Possible variation of voltage between poles and earth can cause current flowing through these capacitors.
- Insulation resistance between poles and earth in operation by connecting one pole to the earth and measuring current flowing between the other pole and earth (see Figure 8).

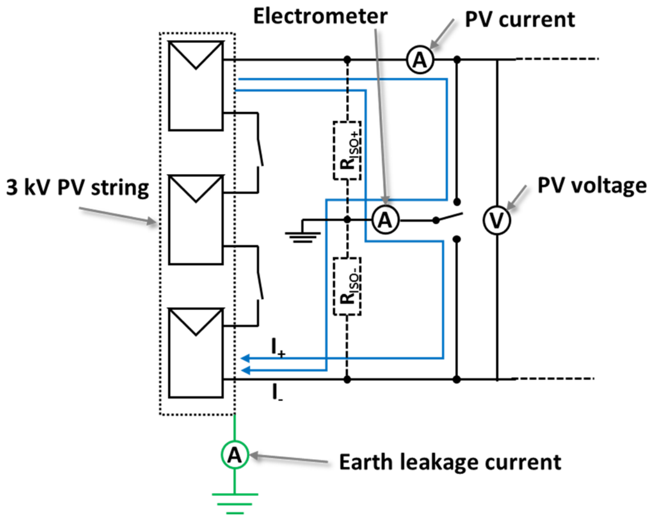


Figure 8 – Measurement to be done on the PV string

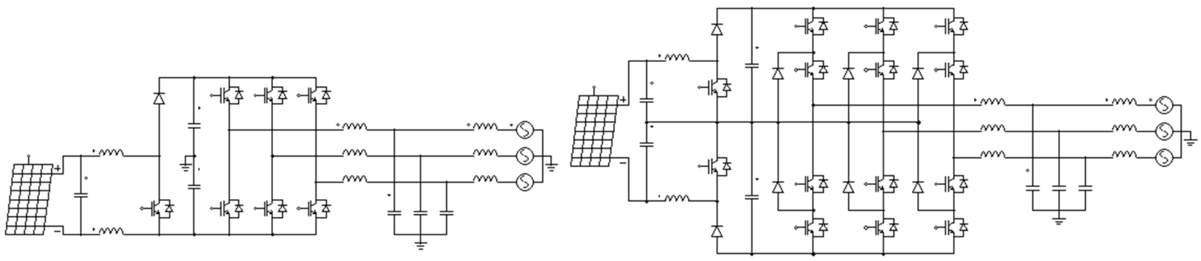
2. Static converter for power injection to the grid

The future work will be to replace the buck chopper by an inverter and to inject the power into the 20 kV_{RMS} three-phase grid via a transformer.

For example, two type of topologies can be proposed:

- A boost chopper (for MPP tracking) followed by a full bridge three-phase voltage-source inverter (VSI). The maximum switched voltage is 3 kV so 10 kV blocking voltage SiC MOSFET can be used.
- Symmetrical boost choppers (for MPP tracking) followed by a 3 levels neutral-point clamped (3L-NPC) three-phase VSI. The maximum switched voltage is the half than in the full bridge version so using of 1.7 kV blocking voltage SiC MOSFET can be envisaged.

Schematics of the two proposed VSI topologies are given Figure 9.



(a) Boost chopper + full bridge VSI (b) Symetrical boost choppers + 3L NPC VSI

Figure 9 – Voltage source inverters to be used for the grid-connected PV conversion stage

VI. Conclusion

Because of the increasing of the power of the PV plant installed in the world and thanks to the SiC high-voltage power semiconductor today available, development of medium or high voltage PV plants can be considered.

An 18 kW, 3 kV demonstrator, using special reinforced insulation PV modules is built at INES site. A DC/DC static converter is firstly used to work the PV generator at its MPP and the power is dissipated in a resistor.

In the future, measurements will be done on the installation to validate – or not – the operation of such a medium-voltage PV plant.

In a second time, the DC/DC converter will be replaced by an inverter based on SiC MOSFET switches in order to inject power in the 20 kV_{RMS} three-phase grid.

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