Development of a 1500Vdc Photovoltaic Inverter for Utility-Scale PV Power Plants

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Abstract— **The increase in size of large-scale photovoltaic plants increases the relative impact of ohmic losses in the dc and ac transmission. On the other hand, the amount of strings also increases, along with the number of combiner boxes and related equipment. This results in increased losses and costs that impose a limit to the competitiveness of PV technology for large power plants. PV plants today are rated at 1000V, which is considered low voltage in IEC and ANSI standards, but in fact, the IEC standard covers up to 1500V in the low voltage category. Going to this maximum voltage will allow for a considerable reduction in current, reducing the system losses on the DC side. On the other hand, a longer string can be achieved, reducing the number of combiner boxes and allowing a rise in the ac voltage. This paper presents the development of a 2.3MW inverter with a maximum DC system voltage of 1500V. A neutral point switch type three-level inverter configuration, so-called T-type three-level inverter, is employed for better conversion efficiency. Simulation results confirm the performance of the 1500V rated inverter.**

Keywords: Photovoltaic inverter; 1500V system; neutral point switch three-level inverter, T-type three-level inverter.

I. Introduction

Regulations and standards for PV plants have developed through the years, and have brought forth enhanced inverter functionalities allowing the connection of large PV plants to high voltage transmission and distribution networks [1][2]. As a result, not only the amount of photovoltaic energy, but also the size of a single plant has been growing, reaching hundreds of MW for a single project in large desert areas.

As the technology becomes mature, there has been a continuous effort in improving the system efficiency and reduce the total cost. This has been exacerbated by the continuous increase in size of single photovoltaic plants, driven by the reduction in cost of PV modules and other components, and on the other hand due to a strong demand for renewable energy.

It has been found that an effective way to achieve these goals is to increase the system voltage. Currently most large scale plants are rated to 1000Vdc, which is the maximum system voltage for most PV modules. This limitation in voltage causes that as the PV plant gets bigger, ohmic losses play a bigger part in the system losses. Also, this voltage constrain impose a limit in the maximum number of modules that can be connected, increasing the number of combiner boxes proportionally to the size of the PV plant. Another important issue of the 1000V system is the MPPT range. Most central inverters have an MPPT range that would not be enough to ensure full production in all conditions through the year in locations with very cold winters and very hot summers, due to the voltage variations of the PV modules caused by variations in module temperature [3].

Although most PV modules, inverters and combiner boxes are rated to 1000V dc maximum, the maximum dc voltage in IEC standards for low voltage equipment is 1500V. This 50% increase in dc voltage will allow a reduction in the dc current, which will reduce the ohmic losses considerably. Also more modules can be connected in series in the string, reducing the amount of combiner boxes. On the ac side, the voltage can be also increased, and the MPPT range can be also wider, which is suitable for locations with cold and hot days. Last, but not least, higher voltage yield to higher power density, allowing a compact design. This paper presents the development of a 2.3MW/2.5MVA inverter with a maximum dc voltage of 1500V, for utility-scale photovoltaic applications. Specifications and design considerations are discussed, with emphasis in the topology of the power bridge. A comparison with a 1000V rated inverter show the benefits of the 1500V system. Simulation results show the satisfactory performance of the inverter and its suitability for large power plants.

II. System Configuration

Table 1 shows the ratings of the developed 1500V inverter. The AC voltage is selected to be 550V. This

TABLE II
COMPARISON BETWEEN 1000VDC AND 1500VDC RATED INVERTER

	1667kW/1000Vdc	2300kW/1500Vdc	ratio
Maximum Input DC Voltage	1000 V	1500 V	1.5
MPPT Voltage Range	605 V - 950V (ΔV=345V)	800 V - 1300V (ΔV=500V)	1.45
Minimum MPPT Voltage	605V	800V	1.32
Current per kW at minimum MPPT voltage $^{(*1)}$	1.65 A/kW	1.25 A/kW	0.76
Current per kW at maximum MPPT voltage $^{(*1)}$	1.05 A/kW	0.77A/kW	0.73
Ohmic losses on the DC side $^{(*2)}$	-	-	0.53 at min MPPT 0.58 at max MPPT
AC Voltage	418 V	550 V	1.32
Dimensions	2286 x 5000 x 1150 mm	2286 x 5000 x 1150 mm	1
Floor space	5.75m^2	5.75m^2	1
Volume	13.14m^3	13.14m^3	1
Output Power	1667kW	2300kW	1.44
Power Density	126.82kW/m^3	174.97kW/m^3	1.38

*1: Losses in the inverter are not considered for simplicity (Both inverters have similar efficiency profiles, so the ratio will not be affected)
*2: Same resistance is considered for comparison purposes

TABLE I
INVERTER SPECIFICATIONS

System Ratings	
Maximum Input DC Voltage	1500 V
Rated Input DC Voltage	925 V
MPPT Voltage Range	800 V 1300V
AC Voltage	550 V
Output Power	2300 kW
Maximum Apparent Power	2500kVA
Maximum Power Factor at Rated Conditions	0.92

Fig. 1. Outline of the 2.3MW photovoltaic inverter.

inverter is transformerless, therefore it requires a step-up transformer that provides galvanic isolation for connection to the power grid. The MPPT voltage range is 800V to 1300V, giving a 500V range suitable for a proper string design in all locations. The maximum power factor when working at rated active power is 0.92. Most utilities require 0.95 at the point of interconnection. A picture of the inverter is shown in Fig. 1.

Table 2 shows a comparison with a similar 1000V photovoltaic inverter rated at 1667kW/1833kVA. The last column shows the ratio between the 1500V inverter and the 1000V inverter for each parameter in order to show the difference between both systems.

Starting the comparison on the dc side, it can be seen that the increase in system voltage yield to a widening on the MPPT range. The 500V range from the 1500V system is 1.45 times wider than the MPPT range for the 1000V system, which ranges from 605V to 950V, that is, a 345V range. The minimum MPPT voltage is increased 1.32 times from 605V to 800V, reducing the current by a factor of 0.76 per kilowatt. That is 3/4 of the current is required for the same power. A similar ratio is confirmed at the maximum MPPT voltage, where the current is reduced to 0.73. Considering the same total resistance in cables, the ohmic losses in the DC transmission are reduced to 53% of the 1000V volt system at the minimum MPPT voltage, which is almost half. A similar situation occurs at the maximum MPPT voltage, where the losses are reduced to 58% of the 1000V system.

On the ac side, the ac voltage is increased from 418V to 550V, which is the same increase achieved in the minimum MPPT voltage. The compared inverters have the same dimensions and therefore the same floor space and volume. Comparing the power density, it can be seen that the 1500V rated inverter has 1.44 times more power than the 1000V rated inverter (2.3MW compared to 1.67MW). Thus, the power density in terms of kW/m^3 increases 1.38 times for the 1500V rated inverter.

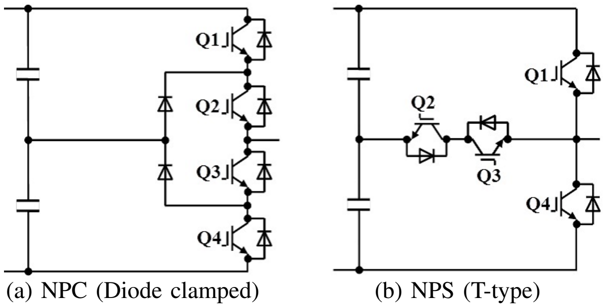

Fig. 2. Three level inverter configurations.

	Q1	Q2	Q3	Q4
S1	ON	ON	OFF	OFF
S2	OFF	ON	ON	OFF
S3	OFF	OFF	ON	ON

Fig. 3. Switching states for NPS inverter configuration.

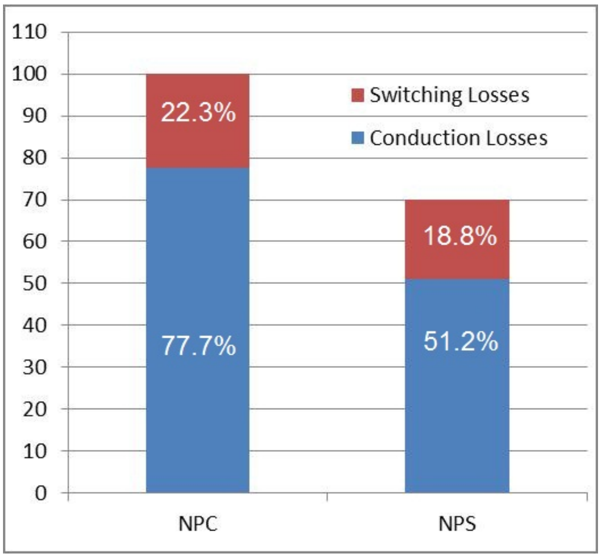

Fig. 4. Comparison of conduction and switching losses for NPC and NPS bridge configuration.

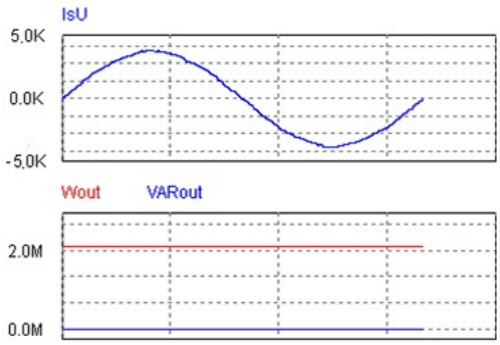

Fig. 5. Current waveform at rated power.

III. Inverter Bridge Topology

Several topologies have been used in 1000V rated photovoltaic applications for the main bridge[4][5]. Among them, several manufacturers are adopting a three-level configuration[6] due to its excellent performance in harmonics, which helps reducing the size of the magnetic components.

There are two main configurations commonly used for a three-level inverter, the diode clamped inverter (NPC in Fig. 2a) and the neutral switch type, which is also known as the T-type (NPS in Fig. 2b). Switching states are the same for both configurations and are shown in Fig. 3 for reference. This 1500V rated inverter uses the NPS three-level inverter shown in Fig. 2b. Switches Q1 and Q4 are rated at 1700V, so that Q1 and Q4 can withstand up to 1500V each. Q2 and Q3 are rated at 1200V. The NPS type offers the advantage of less conduction losses and a simpler configuration than other three-level topologies[7].

An evaluation of conduction and switching losses for the NPC and NPS configurations in a photovoltaic application was performed through calculations and simulations in PSIM. Typical parameters of commercial IGBT modules for a 1500V application were used, assuming that they are controlled via sinusoidal PWM, both with the same fixed carrier frequency. Grid voltage is set to 550V while dc voltage is set to 800V, operating at 100% output power, which is 2300kW.

Losses on the semiconductors are depicted in Fig. 4, conduction losses for the NPC are 77.7% of its total semiconductor losses, which can be attributed to the fact that the current always passes through two devices. On the other hand, for the NPS inverter, the conduction losses are reduced significantly, representing 51.2% compared to the total losses of the NPC. This is because current coming from the positive bus and negative bus passes through only one device (Q1 or Q4). Switching losses are similar in both the NPC and NPS configuration, 3.5% lower for the NPS configuration than that of the NPC.

Combining the conduction losses and switching losses for both configurations, the NPS configuration is 30% more efficient than the NPC. This reduction in overall switching and conduction losses compared to the NPC configuration brings forth better conversion efficiency, which reduces the cooling requirements and helps improving the reliability.

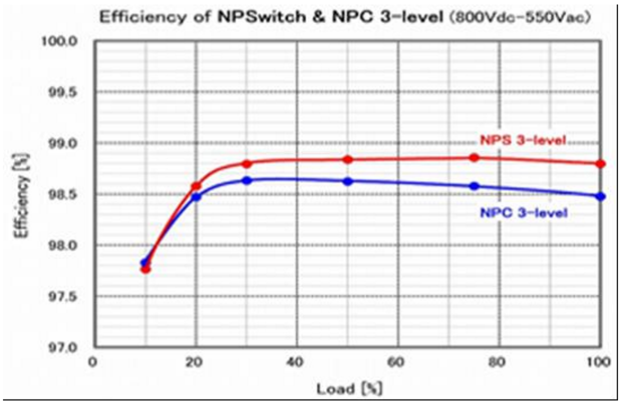

Fig. 6. Conversion efficiency for NPS and NPC configurations at 800Vdc and 550Vac.

IV. Performance Verification

A detailed model of the inverter was done in PSIM including the modeling of the power bridge of section III in order to evaluate the power quality and efficiency. Thus, efficiency results include the results shown in Fig. 4 for the inverter bridge.

Fig. 5 shows simulation results for the NPS configuration with a grid voltage of 550V and a dc voltage of 800V at rated power, which is 2300kW. The current THD for this case is 2.08%, which is compliant with IEEE 1547 and IEEE 519. By using a three-level configuration for the power bridge, a low harmonic distortion can be achieved with a small harmonic filter, which contributes to better efficiency while ensuring compliance to power quality standards. Note that the same power quality performance can be achieved either with an NPC or an NPS configuration and the results will depend on the choosen PWM modulation, switching frequency and filter parameters.

Efficiency for the 1500Vdc inverter was obtained for both the NPC configuration and the NPS configuration. Simulations were done at 800V dc and 550V ac, and results are depicted in Fig. 6.

The inverter using NPS bridge configuration has considerably better efficiency than the NPC configuration. As the output power increases, the difference in efficiency between NPS and NPC becomes bigger. At rated output power, the total efficiency of the NPS inverter is 0.3% better than the NPC. This is due to the fact that the reduction in conduction losses becomes bigger as the output current increases.

The efficiency of the NPS inverter is over 98.8% for most of the operation range, reaching its maximum of 98.85% at about 75% output power. This is not only because of the losses distribution in the semiconductors; the optimization in the design of the passive components is a key factor in achieving a uniform efficiency profile, which is important in photovoltaic inverters since they operate at different power levels during the day depending on weather and irradiance conditions.

V. Conclusion

This paper presented a 2.3MW/2.5MVA photovoltaic inverter rated at 1500Vdc, suitable for large power plants. A detailed comparison based on the specifications of a 1000V rated inverter and the proposed 1500V inverter was done, demonstrating the benefits of the 1500V system which can be summarized as lower losses due to the reduction in current, wider MPPT range and higher power density.

On the other hand, a comparison between NPS (T-type three-level) and NPC (diode-clamped three-level) configuration was performed, modeling the converter in details. It was found that the NPS configuration is superior to the NPC for photovoltaic applications due to its lower conduction losses which yield to better efficiency.

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This Paper was presented in the 2015 International Conference on Renewable Research and Applications (ICERA) Published by IEEE and available in the IEEEXplore Digital Library http://ieeexplore.ieee.org/document/7418531