Technical Solutions and Standards Upgrade for Photovoltaic Systems Operated over 1500 Vdc

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***Abstract*— This paper deals with photovoltaic (PV) systems with operating voltage increased over the value 1500 V in DC, which represents the limit of the current solutions and the actual standard for the PV plant at utility-scale level. The increase of the DC voltage is aimed at reducing the cable energy losses, the number of components and to optimise the layout of the plants, increasing the competitiveness of Medium Voltage PV (MVPV) solutions with rated powers of hundreds of megawatt. The analysis carried out has identified the possible solutions to adopt in order to reach this target and has remarked that today the International Standards are not covering all the aspects of the technical solutions to be introduced in a MVPV plant. This paper indicates the key issues to be addressed by new Standards on some components in order to enable the deployment of MVPV solutions. Finally, the characteristics of an installation at 1500 V DC and some results of tests carried out on the isolation system of a 1500 V PV plant are discussed.**

Keywords*— *Medium Voltage photovoltaic systems, Standards, PV modules, junction boxes, string boxes, DC/DC converter, Inverter, grounding.

I. INTRODUCTION

The number of photovoltaic (PV) systems installed the last decade has significantly increased worldwide [1]. The main drivers for this growth have been:

- various public incentives, given to Renewable Energy Sources (RES) in proportion to the produced energy rather than the investment cost [2];
- the improvement of conversion efficiencies;
- the reduction of the Levelised Cost of Electricity (*LCOE*) as a result of economies of scale.

LCOE indicates the cost of the energy production taking into account the fixed and variable costs (both capital expenditures and operation & maintenance costs), and the amortisation of the initial capital [3]. PV systems reach the so-called *grid parity* when the *LCOE* reaches the cost of the electricity produced from traditional fossil fuels. In this sense, today the bid price of PV electricity is less than 30 c€/kWh in many countries of South America and Middle East Asia. The PV module prices for utility-scale plants have been reported down to 0.4 €/W at the end of 2015 [4]. In 2016, these prices continued to go down, pushed by overcapacities and lower market expectations [5]. According to [6], the installed PV capacity will increase 14-fold by 2040 and the levelised cost of new electricity from PV systems will drop by 66% by 2040.

In this scenario, one of the directions for further progress is the installation of PV plants of bigger sizes. Large-size PV plants include many PV strings, connected in different ways, converted and transformed to reach the point of connection with the external network. However, in these PV plants the DC voltage of the PV strings remains below the conventional Low Voltage (LV) limit (1500 V). When the rated power exceeds 100 MW, the power losses in per cent shall be minimised and the converted energy shall be maximised. The design actions impacting on these two targets are multiple. As an example, currently the conversion efficiency of the mono-crystalline silicon technologies exceeds the 20% threshold for the PV modules, and the DC-AC efficiency is close to 99% for the inverters. Then, the converted energy increases by 25-35% if 1-axis or 2-axis Sun tracking systems are installed. Finally, the power losses inside the cables would decrease potentially by 50-60% if the system voltage of PV generators could be shifted towards a Medium Voltage (MV) level.

This paper considers the possibility of constructing new PV systems in which the DC voltage is higher than 1500 V, with the objective of increasing the competitiveness of the PV plants and reducing the overall costs. This type of solution is indicated here as Medium Voltage PV (MVPV) system. One of the major issues is that, going beyond the LV limit, a lack of Standards could be encountered for some components of the MVPV system. Thereby, the analysis carried out has focused on the technical solutions for the PV plant components, and on the related International Standards, in order to check whether these Standards already cover all the technical solutions enabling the installation of a MVPV system.

The next sections of this paper are organised as follows. Section II recalls the structure of the present PV systems with DC voltage of 1500 V and indicates possible structures of MVPV systems. Section III discusses how the present International Standards cover the needs of the MVPV plant components and solutions. Section IV deals the results of isolation tests carried out on a PV string operating at DC voltage of 2000 V. The last section contains the conclusions.

II. MVPV SYSTEM STRUCTURES

A. Present PV System Solution with 1500 V

Before presenting the technical solutions identified for MVPV systems, a brief description about the most common solution, with 1500 V as system voltage, is provided. Figure 1 shows an example of PV string, composed of 30 modules in series, with system voltage of 1500 V, where the maximum system voltage is calculated considering the maximum open circuit voltage (V_{OC}) of the PV module, according to the extreme environmental condition of the installation site.

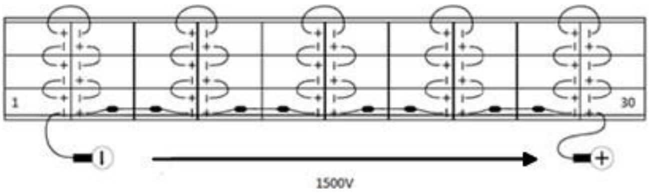

Figure 1 - PV string with 30 modules in series

This is the most common solution for the PV plant at utility-scale levels, where 1500 V is now the standard design, and it definitely took the place of the 1000 V solutions. The 1500 V solution showed remarkable advantages compared to the 1000 V one, in particular considering the Balance of Plant (BoP) costs, that are actually lower, and the lower number of components installed on the field (in particular supporting structures and combined boxes). At present, no solution with DC voltage higher than 1500 V is in operation.

B. Solutions with Voltage Higher than 1500 V

This section summarises three structural solutions than canbe used in order to set up a MVPV system.

B.1. Increasing the number of PV modules in series

This solution consists of increasing the number of PV modules connected in series in a string, reaching DC voltages higher than 1500 V. Considering the same DC power, this solution would allow the reduction on the overall number of the supporting structures, connectors and string boxes, compared tothe 1500 V solution.

Passing from 1500 V to higher voltages means passing from LV to MV for direct voltage/currents. Thereby, all the following components, from PV modules to DC/AC converters,shall be designed and certified to operate in Medium Voltage, according to the applicable MV standards:

- PV modules, including junction boxes and connectors;
- string boxes, including switch and protection devices;
- DC/AC inverters, including DC and AC switches;
- solar cables, from PV modules to string boxes, includingconnectors;
- DC cables, from string boxes to inverters.

This solution does not imply the usage of additional different components with respect to the ones already used on the PV plants.

B.2. Installing a DC/DC boost converter to increase the voltage

In the literature there are several studies [7-9] that apply the use of a DC/DC boost converter to increase the DC voltage overthe LV limit, without modifying the string composition. Thissolution allows to keep the maximum string voltage within thelimit of 1500 V and to decrease the current, so the Joule losses,in the DC cables, between the DC/DC converter and the DC/AC inverter. Furthermore, this solution allows a better MPPT optimisation, compared to a traditional central inverter solution, which could be managed directly by the DC/DC converter [7].

A possible design technical solution could be to integrate theDC/DC converter with the string box. In this scenario only the following components, from string boxes (excluded) to DC/AC inverters, shall be designed and certified to operate in MediumVoltage, according to applicable MV standards:

- DC/AC inverters, including DC and AC switches;
- DC cables, from string boxes to inverters.

This solution implies the usage of a DC/DC converter, whichis an additional component, different with respect to the ones already used on the PV plants.

B.3. Increasing the number of PV modules in series with intermediate grounding

This technical solution is similar to first one (Section B.1), because also in this case the number of PV modules in series isincreased to reach DC voltages higher than 1500 V, but an intermediate grounding of the string is considered in order to keep the two “sub-strings” below the 1500 V (earth-phase voltage).

This solution permits to consider the usage of the 1500 V rated PV modules currently available on the market. However,all the following components, from PV modules (excluded) to DC/AC inverters, shall be designed and certified to operate in Medium Voltage, according to applicable MV standards:

- string boxes, including switch and protection devices;

- DC/AC inverters, including DC and AC switches;
- solar cables, from PV modules to string boxes, includingconnectors;
- DC cables, from string boxes to inverters.

C. Notes on further MVDC Technologies

Together with the study of possible technical solutions for MVPV systems, other similar technological applications have been investigated. In particular all the possible technologies, with at least one section in MV DC, have been considered, in order to find out any common aspect to be extended to MVPV systems.

The following applications have been investigated:

- *Railway traction at 3kV DC*: of course there are big differences between railway systems and PV systems. In the first ones, the power flows through overhead lines, while in the second ones power is generated by PV modules and transmitted through insulated cable lines. Furthermore, in railway systems several moving parts cause big oscillations and vibrations, while in PV systems there are no moving parts, except PV tracking systems (when present). Also, the power can be very different: a PV string can generate moreor less 10 kW, while a single electric locomotive has a power of some MW.

- *MVDC naval systems*: inside large ships the electrical distribution is usually built in MV AC. New solutions with electrical distribution in MV DC have been investigated recently [10], [11]. Furthermore, several studies regarding MVDC naval solutions have been presented [12], [13], [14].In 2010 the IEEE issued a first guideline regarding this kindof applications [15].

- *MVDC networks*: in recent years, several studies have focused on the potentialities of this kind of networks [16], [17]. Technical solutions regarding energy conversion [18],[19], [20] and network stability [21] are currently under analysis. An advanced study carried out at RWTH Aachen University [22], regarding the design of the electrical distribution system of the campus in MVDC, has highlightedpros and cons of the solution.

III. INTERNATIONAL STANDARDS AND CHOICE OF THE COMPONENTS

A. Notes on the International Standards

A detailed analysis on the international regulatory context was carried on, to identify the new reference standards for the design of the PV plants with system voltage higher than 1500 V.This work has investigated also the implications related to the main components of the plant, identifying for PV modules, string boxes, cables and inverter, the current standards that would not be applicable passing to the MV level, and the new ones that could, perhaps, become the new references.

The first step was to compare the photovoltaic application with other applications in the market where the MV DC level iscurrently a standard, as the railway sector. Despite the first lookcan lead to identify many electrical components, used in the railway application, that could be applicable also in the photovoltaic sector, actually it is not the case. In fact, the components used in the railway applications (fuses, cables, switchgears, and so on) are designed to deal with a high level of vibrations and stress. Furthermore, the size and the weight of these components are not definitely “scalable” in photovoltaic plants. In fact, they would have remarkable cost implications and changes on a lot of current equipment, resulting, at the end, in an oversizing of the component itself.

B. Relevant Standards for MVPV Systems

In the current standard and legislation context, the projects are designed according to the Standards CEI 64-8 (for Italy [23]) and IEC 60634 (as an IEC Standard [24]), because these standards apply to LV electric plants. Moving to the MV level (DC voltage), the new reference standard for the design is the IEC 61936-2 [25]. The purpose of this standard is to define common rules for the design and the construction of electrical plants with nominal voltage higher than 1.5 kV DC. This standard partitions the electrical plants in two categories: “opendesign” and “enclosed design”. The components used in the installations of “open design”) have no protection against the direct contacts, while the installations of “enclosed design” guarantee this kind of protection.

Taking into consideration a PV plant, the Standard IEC 61936-2 does not indicate any drastic changes on the layout, compared to the LV plant, because the PV plant, even at the MV level, falls into the “installation of enclosed design” definition.In fact, all the components of these plants are certified for the insulation class type II (EN 61140 art 7.3 [26]), with a minimumlevel of international protection IP2X. For the plants of the category “enclosed design”, the standard does not provide any particular action (i.e., additional fence or minimum safety distance) unlike for the “open design” category.

Finally, the design of the earthing system for electric plants in DC at the MV level does not have any particular indication from the standards. In fact, the IEC 61936-1/2 and the EN 50522 [27] define the requirements for the systems with voltages higherthan 1500 V, however the IEC 61936 is not exhaustive about this topic, and the EN 50522 is valid only for AC plants. Thus, an extension of the EN 50522 is actually desirable.

C. MVPV Components

As a general overview, the purpose of the analysis of the standards referring to the components was to define, for each component, every possible limit to apply the current standards related to voltage level. Actually several standards do not indicate explicitly any reference to the voltage level, because their main scope is related to the product quality, so all these standards are still applicable even over the LV limits.

Focusing on the electrical characterisation and requirements, there is no reference standard, for the photovoltaic application, related to electrical components at MV DC. In the following paragraph, all the standards not applicable will be indicated for each component, highlighting a relevant standard void.

C.1. PV modules

All the technical solutions that will not take the string voltage over the LV limits (i.e., using a DC/DC converter) will not need any different standard for the PV modules than the ones already existing.

It is important to note that the UL standards, used in the US market, explicitly indicate the limit of system voltage at 1500 V, so, in this specific case there will not be any UL standards for higher voltage.

The IEC standards, related to the product qualification and homologation (IEC 61215 [28]), to the safety (IEC 61730 [29]), to the resistance against the main environmental critical conditions (IEC 61701 [30], IEC 62716 [31], IEC 60068-2-68 [32], IEC 62759 [33], and IEC 62782 [34]) and to the PID phenomenon (IEC 62804 [35]), do not indicate explicitly any constraint to the maximum system voltage of the PV module. Almost all these standards require that the manufacturers declare explicitly the maximum system voltage at which the module can work. Furthermore, standards like IEC 62804 are valid only up to the system voltage applied during the test for the product certification. Therefore, there are no constraints on the system voltage value, but the certifications are valid only up to the system voltage used and applied during the certification tests.

Additional issues emerged when the analysis focused on connectors and junction boxes.

The connectors are used to join the PV modules and to make the connections with the pre-parallel boxes (or string boxes). The main standards for these components are the EN 50521 [36], UL 6703 [37], and IEC 62852 [38]. The Standards EN 50521 and IEC62852 are applicable to the connectors for class “A” modules, to be used in photovoltaic applications with system voltage up to 1500 V, while the Standard UL 6703 extends the voltage range up to 2000 V.

There is a similar situation for the junction boxes, where the electric terminations, which collect the current from all the PV cells, are located. The junction boxes shall respect the following standards: EN 50548 [39], IEC 62790 [40], and UL 3730 [41]. Also in this case, the EN and the IEC are applicable for PV modules up to 1500 V DC.

Finally, the design of a PV module for system voltages above 1500 V, would require a complete new design for the junction boxes and the connectors, but also a probable increase of the back-sheet thickness (about 20%, as confirmed by some manufacturers), over than the continue research of new materials.

C.2. Cables

The cables for photovoltaic applications can be partitioned in two different categories: solar cables and non-solar cables. Both types of cables are unipolar, with insulation class II. These cables do not have so stringent standards in terms of voltages. In fact, only few of them (i.e., the EN 50618 [42] or UL 4703 [43]) clearly indicate voltage limits at 1500 V or 2000 V. However, there are many other standards that already allow higher voltage, like the IEC 60502-1 [44] that can be a starting point to review also the EN 50618.

C.3. String boxes

The string boxes are one of the peculiar components of a PV plant, their purpose is to collect and parallel several strings in one cable. Inside the string box there are also sectioning and protection components, which make the string box actually a switchgear. There are two kinds of string boxes, called *active* string boxes and *passive* string boxes. The difference among them is the possibility to monitor actively all the electric parameters and the state of the component itself.

There are many standards applicable to the LV switchgear and the active string boxes, which shall comply with additional requirements, well defined appositely in separate standards, however none of them is applicable for voltage higher than 1500 V DC. When moving to the MV voltage range, the reference standard is the IEC 62271 [45], but unfortunately, this series is related only to AC application, so there is actually a relevant void on the international standards to deal with.

C.4. Fuses and surge protective devices

The most common over-current protection system on the DC side of the PV plant is given by fuses, in particular the protection against the reverse current towards the strings. Therefore, the voltage increase will have impact also on these components. Currently, all the standards related to fuses for photovoltaic applications specify the voltage limit at 1500 V, so a relevant review of those standards is needed. Obviously, there are some other applications where the fuses are widely applied (i.e., railways) at MV voltage on the DC side, but in those cases the specific applications involve particular requirements that would result in a very oversized component (in weight and size), if applied to a photovoltaic plant.

The same considerations are also valid for the surge protective devices (SPDs), because the voltage limit is well defined also for these components and the void on the standards is quite relevant.

C.5. Inverter

Finally, the analysis was focused on the inverter, and more generally on the entire Conversion Unit. There are many standards that define the requirements for the inverter for photovoltaic application, and all of them clearly specify the limit of the LV application. In particular, the main standards IEC 62109-1 [46] referring to the protection systems, IEC 60364-7 [24] and IEC 60947 [47] become not applicable when exceeding the LV limit. Concerning the safety issue, the IEC 62109-2

[48] is still applicable even over 1500 V. Furthermore, in this context, the technical committee already started to approach this problem, and the new standard IEC 62477-2 [49] is currently under development.

Looking at the re-design of the inverter for MV DC applications, it is important to note that many inverters already have a 3-L NPC topology, with a bridge able to deal with a DC-link voltage of 2400 V (maximum value), due to the fact to have 2 IGBT of 1200 V connected in series. Therefore, not considering the regulatory void, this kind of typology would be still valid to operate also at 2000 V, exceeding the LV limit.

IV. EXPERIMENTAL TESTS ON THE INSULATION RESISTANCE

As described in Section II.B.1, one technical solution investigated consists of connecting more modules in series, to obtain a "longer" electrical string to reach the desired system voltage. This solution will affect, of course, the equivalent insulation resistance (versus the ground potential) of the total string, proportionally to the number of modules connected in series. Therefore, the aim of this experimental activity was to check the insulation resistance of each module and of the string, in order to investigate if the standards requirements are still fulfilled [50]. The IEC 61215 [28] and the IEC 60634 [24] specify the minimum requirement for the insulation resistance times the area of the module for the single module and the insulation resistance for the total string:

- $R_{ins\_mod} \geq 40$ MΩ·m^2 (IEC 61215)
- $R_{iso\_string} \geq 1$ MΩ (IEC 60634)

The insulation resistance of each module is different for each module even among modules with the same technology, power class and same production branch, due to unavoidable differences that can occur in the production chain. However, for a theoretical approach, the hypothesis to consider the same insulation resistance for all the modules is quite reasonable, even because these differences can be negligible compared to the value of the resistance itself.

Calculating the equivalent insulation resistance of a string of PV modules is just a parallel of the all insulation resistances of each PV module, resulting in:

$$R_{\mathrm{iso}\_string\_\mathrm{n}} = R_{\mathrm{iso}\_mod} / \mathrm{n} \qquad (1)$$

where n is the number of PV modules connected in series.

To perform the test, 8 commercial PV modules from Risen Solar Technology have been used (model RSM72-6-320P). The test conditions applied are the ones described in the abovementioned standards. The resulting average insulation resistance (considering the 8 PV modules under test) is about 67.6 GΩ at 1500 V, while the insulation resistance times the area of the module is about 130.9 GΩ·m^2. The insulation resistance of the string composed of these 8 modules is 8.4 GΩ. This value is quite in line with the theoretical formula (1), so it is possible to adopt this formula to calculate the insulation resistance for strings composed of more modules. In particular, assuming the realistic value of 50 V for the maximum open circuit voltage of the module V_{OC}, it is possible to reach 1500 V by connecting 30 modules in series, or 2000 V by connecting 40 modules in series. The relative insulation resistance for both cases are indicated in (2) and (3):

$$R_{\mathrm{iso}\_string\_30} = R_{\mathrm{iso}\_mod} / 30 \qquad (2)$$

$$R_{\mathrm{iso}\_string\_40} = R_{\mathrm{iso}\_mod} / 40 \qquad (3)$$

By using the average value measured for the R_{iso_mod}, the results are:

$$R_{\mathrm{iso}\_string\_30} = 67.6/30 \text{ GΩ} = 2.25 \text{ GΩ}$$

$$R_{\mathrm{iso}\_string\_40} = 67.6/40 \text{ GΩ} = 1.69 \text{ GΩ}$$

The values obtained are well above the limit indicated by the standard (≥ 1 MΩ).

V. CONCLUSIONS

In order to look for solutions to improve the competitiveness of the photovoltaic plants, in terms of cost reduction and production increase, a deep analysis was done investigating the technical solutions to increase the system DC voltage over the LV and analyse the new regulatory context applicable. Currently the most common level of system voltage is set to 1500 V, at least for utility-scale plants. Exceeding this limit would mean to "play" in a different framework, due to the passage from the LV to the MV side. The study has identified three technical solutions to achieve this target, and has analysed all of them on a real case of design, on an existing PV plant. All the details are available in [51] and it is possible to highlight that the solutions described in Section II.B.1 and Section II.B.3 are the best technical solutions, in terms of cables energy loss, components reduction and plant layout. Therefore, increasing the system voltage can lead to cost reduction and increase of the energy yield, resulting to an increase of competitiveness for photovoltaic plants. Furthermore, an experimental activity was performed in order to check the impact to have “longer string” on the insulation resistance of the string itself. The results have showed a very good level of insulation resistance, even with more modules connected in series, compared to the 1500 V solution.

The technical analysis was also accompanied by a regulatory context analysis, in order to define the new framework passingon MV side for the DC part of the plant. The results have shownthat some different standards should be applied, than the currentones, in particular for the plant design (i.e., IEC 61936-2) and many standards for the components certifications, related to theproduct quality, safety and performance, remain still applicable. However, there is a relevant regulatory void, because many standards, for the components design and certification are not still valid when exceeding the 1500 V. This problem will impact, in particular, on:

- junction boxes and connectors of the PV module (no standard applicable over 1500 V);
- fuses and SPDs;
- string boxes (no standard for switchgear at MV level for DCapplication);
- inverter.

Therefore, the need for a quick regulatory adjustment is evident in order to define the proper indications and avoid the confusion that could emerge from the lack of specific rules.

REFERENCES

[1] European Photovoltaic Association, “Global Market Outlook,” p. 58, 2017.

[2] G. Chicco, V. Cocina, A. Mazza, and F. Spertino, “Data Pre-Processing and Representation for Energy Calculations in Net Metering Conditions”, IEEE EnergyCon 2014, Dubrovnik, Croatia, 13-16 May 2014, pp. 413– 419.

[3] C. Kost et al., “Levelized cost of electricity - Renewable energy technologies”, Fraunhofer ISE Study, November 2013, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf

[4] IEA, “International Energy Agency Photovoltaic Power Systems Programme. Trends 2017 in Photovoltaic Applications”, Report IEA PVPS T1-30:2016 http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_Trends_2017_in_Photovoltaic_Applications.pdf

[5] Gestore Servizi Energetici (GSE), “Solar Photovoltaic – Statistical Report2016,” (in Italian), 2016, https://www.gse.it/.

[6] Bloomberg New Energy Finance, “The executive summary of New Energy Outlook 2017”, June 15, 2017, https://about.bnef.com/new- energy-outlook/#toc-download.

[7] H. Choi, M. Ciobotaru, M. Jang, and V.G. Agelidis, “Performance of Medium-Voltage DC-Bus PV System Architecture Utilizing High-Gain DC–DC Converter”, IEEE Transactions on Sustainable Energy, vol. 6, no. 2, pp. 464–473, 2015.

[8] H. Choi, W. Zhao, M. Ciobotaru, and V.G. Agelidis, “Large-Scale PV System based on the Multiphase Isolated DC/DC converter”, 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), pp. 801–807, 2012.

[9] H. Choi, M. Ciobotaru, and V.G. Agelidis, “High Gain DC/DC Converter for the Grid Integration of Large-Scale PV Systems”, IEEE International Symposium on Industrial Electronics, vol. 2, pp. 1011–1016, 2012.

[10] D. Bosich, A. Vicenzutti, R. Pelaschiar, R. Menis, and G. Sulligoi, “Toward the future: The MVDC large ship research program”, AEIT International Annual Conference, Naples, Italy, 14-16 October 2015.

[11] D. Bosich, “Medium Voltage DC integrated power systems”, Università degli Studi di Padova, 2014.

[12] U. Javaid, D. Dujic, and W. Van Der Merwe, “MVDC marine electrical distribution: Are we ready?,” IECON 2015 - 41st Annu. Conf. IEEE Ind. Electron. Soc., pp. 823–828, 2015.

[13] A. Shekhar, L. Ramirez-Elizondo, and P. Bauer, “DC microgrid islands on ships”, 2017 IEEE Second Int. Conf. DC Microgrids, no. August, pp. 111–118, 2017.

[14] R. E. Hebner, X. Feng, R. Hebner, A. Gattozzi, S. Strank, A. Mor, L. Ramírez-Elizondo, and P. Bauer, “Electric Cables in Ships and Cities-Can Higher dc Voltage be Imposed as Compared to ac ?”, Energy Open International Workshop, 2017.

[15] IEEE Std. 1709-2010, “IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships”, November 2010.

[16] G. Bathurst, G. Hwang, and L. Tejwani, “MVDC - The New Technology for Distribution Networks,” 11th IET Int. Conf. AC DC Power Transm., 2015.

[17] T. T. Nguyen, H. J. Yoo, and H. M. Kim, “A comparison study of MVDC and MVAC for deployment of distributed wind generations,” IEEE Int. Conf. Sustain. Energy Technol. ICSET, pp. 138–141, 2017.

[18] A. Shekhar, E. Kontos, L. Ramírez-Elizondo, A. Rodrigo-Mor, and P. Bauer, “Grid capacity and efficiency enhancement by operating medium voltage AC cables as DC links with modular multilevel converters,” Int. J. Electr. Power Energy Syst., vol. 93, pp. 479–493, 2017.

[19] Y. Chen, S. Zhao, Z. Li, X. Wei, and Y. Kang, “Modeling and Control of the Isolated DC-DC Modular Multilevel Converter for Electric Ship Medium Voltage Direct Current (MVDC) Power System,” IEEE J. Emerg. Sel. Top. Power Electron., vol. 5, no. 1, pp. 124–139, 2017.

[20] Y. Lee, G. Vakil, R. Feldman, A. Goodman, and P. Wheeler, “Design Optimization of a High-Power Transformer for

Three- Phase Dual Active Bridge DC-DC Converter for MVDC Grids", 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), 19-21 April 2016.

[21] A. Korompili, A. Sadu, F. Ponci, and A. Monti, "Flexible Electric Networks of the Future: Project on Control and Automation in MVDC grids," Int. ETG Congr. 2015, November 17-18, Bonn, pp. 556–563, 2015.

[22] F. Mura and R. W. De Doncker, "Preparation of a Medium-Voltage DC Grid Demonstration Project," in E.ON Energy Research Center Series, First., vol. 4, no. 1, Aachen, Germany: RWTH AACHEN University, 2012, pp. 1–32.

[23] CEI 64-8, "Electrical installations at voltage not higher than 1000 V in alternating current and 1500 V in direct current" (in Italian), 2012.

[24] International Electrotechnical Commission, Standard IEC 60364, "Low- voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions", fifth edition, November 2015.

[25] IEC 61936-2, "Power installations exceeding 1 kV a.c. and 1,5 kV d.c. - Part 2: d.c.", IEC TS 61936-2:2015, 5 March 2015.

[26] EN 61140, "Protection against electric shock - Common aspects for installation and equipment", 2016.

[27] CEI EN 50522, "Earthing of power installations exceeding 1 kV a.c.", 2011.

[28] IEC 61215, "*Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval"*, 2nd edition, 2005.

[29] IEC 61730, "Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction", 2016.

[30] IEC 61701, "Salt mist corrosion testing of photovoltaic (PV) modules", 2011.

[31] IEC 62716, "Photovoltaic (PV) modules - Ammonia corrosion testing", 2013.

[32] IEC 60068-2-68, "Environmental testing - Part 2-68: Tests - Test L: Dust and sand", 1994.

[33] IEC 62759, "Photovoltaic (PV) modules - Transportation testing - Part 1: Transportation and shipping of module package units", 2015.

[34] IEC 62782, "Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing", 2016.

[35] IEC 62804-1, "Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 1: Crystalline silicon", 2015.

[36] EN 50521, "Connectors for photovoltaic systems - Safety requirements and tests", 2008.

[37] UL 6703, "Standard for Connectors for Use in Photovoltaic Systems", 2014.

[38] IEC 62852, "Connectors for DC-application in photovoltaic systems - Safety requirements and tests", 2014.

[39] CEI EN 50548, "Junction boxes for photovoltaic modules", 2011.

[40] IEC 62790, "Junction boxes for photovoltaic modules - Safetyrequirements and tests", 2014.

[41] UL 3730, "Standard for Photovoltaic Junction Boxes", 2014.

[42] CEI EN 50618, "Electric cables for photovoltaic systems", 2014.

[43] UL 4703, "Standard for Photovoltaic Wire", 2014.

[44] IEC 60502-1 "Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) -Part 1: Cables for rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um =3,6 kV)", 2004.

[45] IEC 62271, "High-voltage switchgear and controlgear", 2015.

[46] IEC 62109-1, "Safety of power converters for use in photovoltaic power systems - Part 1: General requirements", 2010.

[47] IEC 60947-3, "Low-voltage switchgear and controlgear - Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units", 2008.

[48] IEC 62109-2, "Safety of power converters for use in photovoltaic power systems - Part 2: Particular requirements for inverters", 2011.

[49] IEC 62477-2, "Safety requirements for power electronic converter systems and equipment - Part 2: Power electronic converters from 1 000 V AC or 1 500 V DC up to 36 kV AC or 54 kV DC", 2018.

[50] J. Flicker and J. Johnson, "Photovoltaic ground fault detection recommendations for array safety and operation," Solar Energy, vol. 140, pp. 34–50, 2016.

[51] L. Scarpa, "New design solutions for photovoltaic systems with voltage higher than 1500 V" (in Italian), M.S. Thesis, Politecnico di Torino, Italy, December 2017.