An Overview Of Photovoltaic Power Plant (PV) Connection To HVDC Grid

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***Abstract*— Solar energy is considered one of the most important alternative and renewable energies for the production of electricity, so that solar power plants work to produce direct current, which is then converted into alternating current through DC-AC converters and linked to power transmission networks of alternating current. But since most of the large solar PV plants are built in areas far from the load, the world is moving today to transfer power directly from solar panels to high voltage HVDC grid, due to the advantages that HVDC provides such as lower transmission loss, low cost and higher efficiency compared to HVAC. In this paper we present Advantages of connecting PV stations directly to the HVDC network instead of the HVAC, an overview of recent studies dealing with Photovoltaic Power Plant Connection to HVDC Grid and PV-HVDC systems comparison in terms of DC-DC converters types and system configurations.**

Keywords*— *Photovoltaic solar power plants (PV), HVDC Grid, DC to DC converter, electric power transmission HVDC.

I. INTRODUCTION

Given that fossil energies are threatened with depletion and at the same time the demand for electric energy is increasing in various parts of the world, this prompted the search for alternative energies that could compensate for this shortage. Solar energy is considered one of the most important of these non-permeable and renewable sources, as it is characterized by a DC output current. This makes it very suitable to be connected to the HVDC transmission network instead of HVAC according to its ability to transmit over high distances with unlimited high voltages as well as lower transmission losses and therefore low cost, asynchronous interconnections[1][2], and long submarine cable crossings[1][2].

The HVDC-connected PV system consists of three main parts: the arrays, which work to produce continuous electricity depending on solar radiation and temperature, then DC-DC converters, which work to raise the DC voltage from low or medium to high voltage, and the HVDC grid. Researchers presented a set of studies in this area. In this paper we present the advantages of connecting a PV plant to the HVDC transmission network instead of HVAC, an overview of recent studies dealing with Photovoltaic Power Plant Connection to HVDC Grid and the comparison between these systems.

II. ADVANTAGES OF CONNECTING A PV PLANT TO THE HVDC GRID

The Solar photovoltaic energy is one of the many types of renewable energies that can be relied upon as an alternative energy to the fossil energies that are threatened with exhaustion. This is what we notice in recent years, photovoltaic plants have spread rapidly in various countries of the world due to their simplicity and ease of implementation of control, in addition to being clean energy devoid of any emissions that cause environmental pollution and global warming, unlike fossil energies.

Solar energy depends mainly on radiation and temperature to generate electricity so that it produces a DC current. To transfer this energy in the traditional case, the current is converted from DC to AC, using a DC/AC inverter, and then passed through transformers to raise the voltage until it matches the transmission network HVAC. However, because photovoltaic plants are often built in areas far up to 400 km or more from places where electric energy is consumed, the HVAC system results in losses for transmission lines and a limitation in the amount of energy that can be transmitted, meaning the greater the transmission distances, the greater the losses, Cost increases and efficiency decreases[3]. In addition to the harmonic resonance problem [4], issues with reactive power adjustment. Moreover, the ac harmonic filters and reactive power banks cover a large area[5].

To overcome the mentioned obstacles, and since photovoltaic power plants generate DC energy, the researchers worked to connect the solar power plants directly with the HVDC transmission network without converting them to an alternating current system and then transferring them through the use of DC-DC converters instead of the DC-AC inverter. These converters have the ability to raise the voltage to the level required to connect them to the HVDC network. The PV-HVDC system consists of three basic stages. The first stage is PV arrays, whose role is to generate DC electricity. The second stage is DC-DC converters, as they work to raise the output voltage of photovoltaic panels from a weak and unstable level to a stable and controlled high level commensurate with the value of the voltage of the HVDC transmission network. In addition, they provide galvanic isolation. The third stage is the high voltage transmission lines for the transmission of electrical energy. The importance of this proposal lies in the transmission advantages offered by the HVDC transmission system with photovoltaic stations compared to HVAC, such as:

- reduce the size and cost of filters [6].
- minimize the number of power conversion connections [7].
- improve the overall efficiency of the system.
- possibility of transmitting electrical energy over very long distances and in unlimited quantities.
- reduce transportation losses and thus lower cost compared to HVAC.
- moreover, there is no hindrance to stability for the HVDC system.
- simplicity of control compared to HVAC.
- transmission of electrical energy over distances greater than 400-700Km without additional losses.
- ability to transmit electric power over long submarine cable distances greater than 50-km.

III. LITERATURE REVIEW OF PV-HVDC SYSTEM

To Connect Large-scale photovoltaic to the HVDC transmission grid high voltage PV modules and a large capacity and high step-up ratio DC-DC converter, accordingly, in reference [8] a centralized DC/DC converter based on Boost Full Bridge Isolated DC /DC Converter with The active clamp circuit is presented. This topology has the potential to provide galvanic isolation with high output voltage, high power density and high switching ratio. The modules are connected by the input parallel output series IPOS so that the latter is useful in being able to easily achieve high output voltage and power suitable for the HVDC network. The authors made a current close loop that has been added to the inner input with the aim of balancing the input current and output voltage with respect to the modules. In order to validate the proposed topology, Xinke Huang et al implemented a BFBIC converter with output voltage and power equal to 5KV and 50KW respectively. Then a converter platform was built by connecting four modules via IPOS in order to obtain ±10kV/200kW, and the results were proven Its compatibility with theoretical analysis so that the maximum efficiency reaches about 95.61%.

Also, Xinke Huang et al proposed a cascaded DC/DC converter structure based on an input parallel output series IPOS module based on a boost full-bridge isolated topology in [9]. The active clamp circuit (S0, CC and boost inductor L) is also intercalated with the proposed structure in order to achieve zero voltage switching (ZVS) which helps to reduce switching losses and improves efficiency. In reference [9] The authors have presented an equalization control approach for distributed modules in order to balance the input current and output voltage between the modules and thus provide for normal operation. In order to validate the proposed topology, Xinke Huang et al implemented a BFBIC converter with output voltage and power equal to 5KV and 80KW respectively. Then a converter platform was built by connecting fourteen modules via IPOS in order to obtain ±30kV/1MW, and the results were proven Its compatibility with theoretical analysis so that the efficiency reaches about 97%.

While in the literature [10], Changbin Ju et al presented a full-bridge isolated converter(FBIC) that achieves isolation between input and output and provides a high step-up ratio in addition to achieving high output voltage. Instead of connecting units in series, the authors relied on the input parallel output series IPOS, this makes it suitable for HVDC network connection. The authors presented the proposed converter double loop control strategy. In order to validate the proposed topology, Changbin Ju et al implemented the proposed topology simulation with power equal to 12KW, and the results showed good performance and good response speed.

To connect the DC voltage output from the photovoltaic panels directly to the HVDC network, Guoen Cao et al proposed in the study [6] a DC-DC converter system consisting of two parts. The first part is distributed MPPT converter, where a non-isolated Interleaved boost converter is proposed at this stage in order to reduce high power losses due to Partial shading of PV arrays in addition to reducing input and output ripples. The second part is a modular centralized DC-DC converter which is an isolated High Frequency LLC topology with input-parallel-output-series with the aim of achieving a large step-up voltage gain, soft switching (ZVS and ZCS) resulting in reduced switching losses and thus, high efficiency of the proposed converter. In order to validate the performance and reliability of the proposed topology, Guoen Cao et al implemented simulation and experimental of the proposed structure with output voltage and power equal to 400V and 3KW respectively, and the results were proven Its compatibility with theoretical analysis and its ability to achieve Soft switching with very low authorization losses.

To connect large-scale PV systems directly to the HVDC network instead of the AC networks, Javier Echeverría et al in [7] proposed a two-stage DC-to-DC converter system based on MMC. In the first stage, the MPPT DC-DC converters, which is an interleaved flyback, which allows the application of the MPPT tracking algorithm as it can from working under high switching frequencies, the latter also provides galvanic isolation between the photovoltaic panels and the second stage. so that the second stage is a multi-modular cascaded of half-bridge chopper dc-dc converter (DC-MMC) that provides an output voltage that can connect to the HVDC network, A DC-link capacitor attached to each MPPT converter feeds each dc-MMC cell. The authors also introduced a phase-shifted PWM controller to reduce the current ripple at the output by reducing the steps in the output voltage. The proposed structure enables the implementation of an individual MPPT and thus the increase in power. The control strategy PHASE-SHIFTED TRACKING PWM has been suggested In reference [11] instead of PS-PWM in order to achieve less undulating and more stable outputs and thus improve the efficiency of the system, the authors here presented a comparison between the simulation results of the proposed system with the PS-PWM and TPS-PWM algorithms. The comparison proved the validity of the analysis and the theoretical results. Moreover, the performance of the proposed structure was experimentally confirmed.

For connecting DC series-parallel photovoltaic (PV) plants to the high voltage DC network the authors proposed a new cascaded DC-DC converter based on input parallel and output series (IPOS) in [12]. It consists of a Quasi Z-Source circuit QZS and a full bridge isolated converter FBIC with leakage inductor Lr, which improves power capacity and output voltage adjustment range. The proposed converter works as a single block. The perturbation and observation (P&O) algorithm is used to track the MPPT for each PV array. The proposed converter achieves work in voltage boost mode and also in buck mode by using a single-stage energy conversion. Phase shifting is implemented shoot through two variable coordination control strategies for the proposed Topology. The converter employs a utility duty cycle control approach for global MPPT. In order to balance the input current and output voltage for all modules, the authors implemented a voltage compensation close loop, while modules putting in and cutting out control are used to extend the output voltage tuning. To verify the proposed topology's performance and reliability, as well as its ability to achieve a dynamic response during radiation change and provide global MPPT, Xinke Huang et al ran a simulation with output voltage and power of 20kV and 500KW, respectively, and then built a system by connecting three modules via IPOS to achieve 60kV/1.5MW. The results proved the efficiency of the proposed converter, its good performance, and its ability to provide global MPPT under variable radiation conditions, which is consistent with the theoretical analysis.

The authors in the study [13] describe a new configuration for a multi-terminal offshore wind farm-based VSC-HVDC and large scale solar system based on the modified unified adaptive linear neuron (Adaline) algorithm. In the study, a large-scale solar power plant was directly connected to the VSC-HVDC, using a multi-level dc-dc converter. MPPT is executed for each converter individually and the perturbation and observation (P&O) algorithm is based on this control.

IV. COMPARISON OF THE SYSTEMS OF PV- HVDC

In this comparison, the focus is on the basic structure and the beating heart of the PV connected to an HVDC grid, which is the topology of the DC-DC converters used in the previous literature to raise the voltage of the photovoltaic to a high value and controlled and that allows being connected with the HVDC network.

Figure 1 shows the DC-DC structure proposed in ref. [7][11] . The proposed converter consists of an isolated flyback converter in order to achieve galvanic isolation and allow the implementation of the MPPT connected with a converter (DC-MMC) [11]. Its advantage is to raise the voltage value to HV by connecting a group of units in series with each other instead of relying on the transformer's conversion ratio and the operating cycle, because of the risks that may be associated with it, such as a sudden rise in current, which negatively affects the transfer switches and the performance of the converter. However, the proposed system has a large volume as it consists of two phases as well as a DC-MMC converter which requires hundreds of units in order to boost the voltage to HVDC and thus increase the cost moreover it entails complex control.

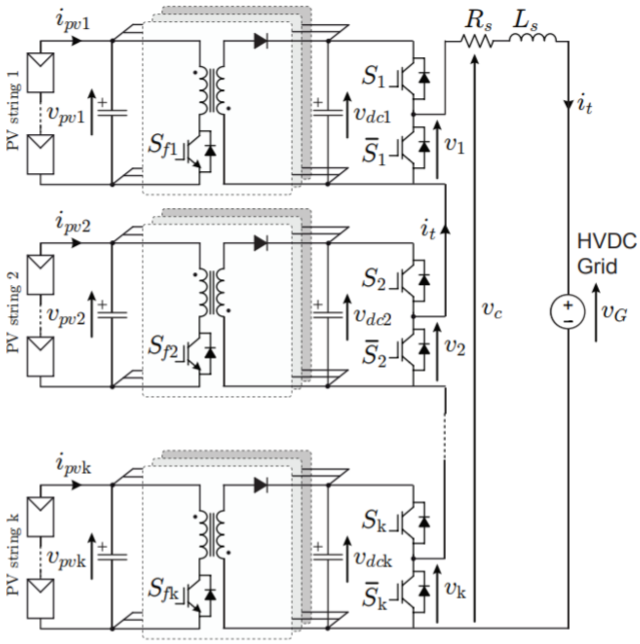

Fig. 1. The suggested PV-DC-MMC system is based on k series linked half-bridge choppers and a flyback MPPT stage with interleaved flybacks.

As for reference [6], two stages were relied upon in order to raise the voltage to the required level as shown in Figure 2. First, an interleaved of the boost converter was used to implement the MPPT and raise the voltage from weak to medium. In the second stage, the LLC full bridge isolated DC-DC converter was released upon, as it raises the voltage to a high level and provides galvanic isolation for the devices. The latter is characterized by reducing EMI and increasing high power density[14] in addition to the ability to work under high switching frequencies[14] is accompanied by reduced switching losses due to its ability to achieve soft switching ZVS switches and ZCS fuses, thus increasing the efficiency and reliability of the system. But one of the drawbacks of the structure is that it depends on two stages, which translates into an increase in size and cost, in addition to the fact that the resonant circuits contribute to the complexity of the circuit and control.

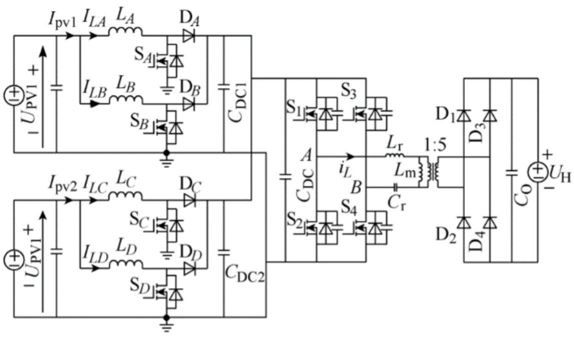

Fig. 2. Proposed LLC converter with interleaved boost converter based on IPOS connection

As for references[8] , [9] and [12], a boost full bridge isolated converter has been relied upon in order to raise the voltage of weak photovoltaic panels to a high level that allows the station to be connected directly to the HVDC transmission network. It also achieves high output power and capacity and a high escalation ratio [8]. Moreover, the references mentioned in this paragraph relied on IPOS to connect the units instead of connecting them in series, as it is characterized by the ability to collect higher voltages, lower switching losses, and increase the reliability and efficiency of the system compared to linking them in series. It also achieves lower volume and cost compared to DC-MMC converters. A boost full bridge isolated converter based on an active clamp (S0, CC, L) is relied on in [8] [9], and Consists of one stage non-discrete block in contrast to previous references. It has better potential to achieve high output voltage and high switching ratio with limited switching losses thanks to the active clamp circuit which is able to provide ZVS soft switching of the converter, which is also lower in cost compared to previous cases and better in reliability and performance. Figure 3 Shows a boost full bridge isolated DC-DC converter based on the active clamp circuit.

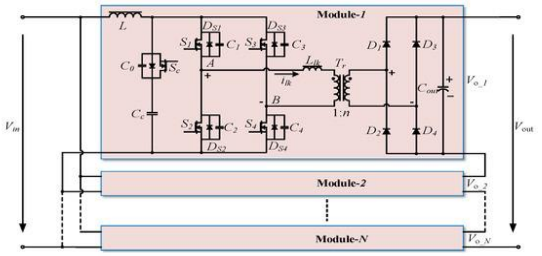

Fig. 3. The IFBC converter with an active clamp circuit based on IPOS connection

While in [12] the Quasi Z-Source (L1 L2 C1 C2 and Dz) full bridge isolated converter is presented. Consists of one stage. The QZS-IFBC converter has a high output voltage and ramp-up ratio and can operate in boost mode (shoot / non-shoot through states) and buck mode. An additional switching state dubbed a "shoot-through" condition is used by the impedance network to give extra boost capability [15]. The shoot-through duty cycle controls the variation of the PV panel's output voltage[16]. The proposed converter does not contain additional switches other than the switches of a full-bridge converter. Moreover, the QZS circuit does not require a control signal, reduces voltage stress on the switches and provides continuous input current, and because it is based on one stage unlike previous structures, it is also characterized by a smaller size and lower cost And good efficiency. But the series diode DZ, L1 and L2 in the qZS network produce the conduction loss [17]. Figure 4 Shows a boost full bridge isolated converter based on the Quasi Z-Source circuit.

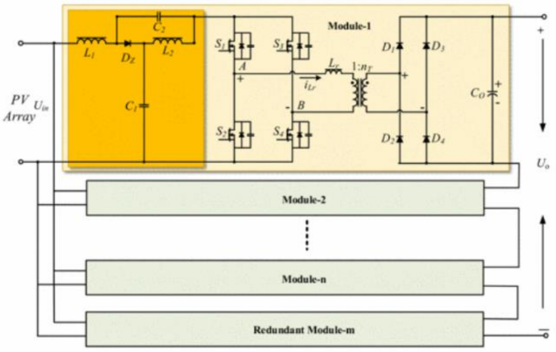

Fig. 4. The QZS-IFBC converter based on IPOS connection

V. MPPT TECHNOLOGY

Photovoltaic energy is one of the most important renewable energies and the most widespread in recent years, but it suffers from sudden fluctuations in the resulting energy due to continuous changes in radiation and temperature, in addition to partial misinformation and thus the inability to extract the full energy from photovoltaic panels. Therefore, the researchers introduced MPPT technology, which works to achieve the maximum power point that can be saved from photovoltaic panels[18][16]. This tracker often needs a switching converter [18]. There are several algorithms that are used to implement MPPT to track the maximum power point of photovoltaic panels [19], including Perturb and Observe, Incremental Conductance, sliding mode control and fuzzy logic control.

See Table. I. For A Comparison Of PV-HVDC Comparison In Terms Of Dc-Dc Converters Types And System Configurations.

TABLE I. PV-HVDC SYSTEMS COMPARISON IN TERMS OF DC-DC CONVERTERS TYPES AND SYSTEM CONFIGURATIONS

Ref	**DC-DC Converter**		**MPPT**	**Control**	**Switching frequency**	**Type de connected**	**Soft-switching**	**Output voltage and power of the proposed converter**	**Output voltage and power of system**
	MPPT Converter	***step-up converter***							
[9]	boost full-bridge isolated		P&Q	distributed module equalization control strategy	5 kHz	IPOS	yes	5 kV/80 kW	±30 kV/1 MW
[8]	boost full-bridge isolated		--	input current close loop	3.3kHz	IPOS	yes	5 kV/50 kW	±10 kV/200kW
[10]	LC full-bridge isolated		--	dual-loop control strategy based on PI	20kHz	IPOS	--	12kW	1.2kv/ 12kW
[6]	Interleaved boost	LLC full-bridge isolated	IC	fixed switching frequency modulation	20kHz 100kHz	IPOS	yes	100V	400V/3kW
[7]	interleaved flyback.	-multi-modular cascaded dc-dc converter (dc-MMC)	P&Q	PS-PWM	5kHz	series	--	1.5kV	10.5kv
[11]	interleaved flyback.	multi-modular cascaded dc-dc converter (dc-MMC)	P&Q	PST-PWM	1 kHz	Series	--	--	0.14kv/1.7kw
[12]	QZS- full-bridge isolated converter		P&Q	phase shift	--	IPOS	--	20kV/500kW	60kV/l.5MW
[13]	multi-level dc-dc converter		P&Q	PI	--	series	--	--	--

VI. Conclusion

Due to the growing interest in the PV-HVDC system for the generation and transmission of electrical energy, as well as the expansion of research in this field, this paper has dealt with the advantages of connecting PV stations directly to the HVDC network instead of HVAC, such as low cost, simplicity of control, reliability and increased system efficiency. Also, an overview of the previous literature was presented that dealt with the PV-HVDC grid system. In addition, a comparison was made between the systems presented in the literature. This comparison focused on the main part of the PV-HVDC system, which are the DC-DC converters used for the purpose of raising voltage from low voltage unstable to high level controlled and suitable for the HVDC network.

Acknowledgment

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