A Distributed DC Grid-Connected PV System with Autonomous Output Voltage-Sharing Control Based on Three Converters

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Abstract: This paper proposes a distributed dc grid-connected photovoltaic (PV) generation configuration and control strategy based on hybrid-connected three-port converters (TPCs). The proposed configuration and control strategy achieve distributed maximum power point tracking (MPPT) and autonomous voltage sharing control. Multiple modular pulsewidth modulation plus phase-shift (PPS) controlled TPCs with soft switching and low voltage stress are used in the proposed system. To achieve individual MPPT, each TPC's input port is connected to an independent PV energy source, and the output ports of these TPCs are connected in series to interface with a high-voltage (HV) dc bus, while the bidirectional ports are connected in parallel to build a low-voltage (LV) dc bus. The power mismatch of input sources can be transferred among these TPCs via the LV dc bus, and power and voltage balancing at the HV output side can be realised. Output voltage sharing is realised by regulating the voltage reference of a bidirectional port in a linear relationship with the output voltage, with only the module's own voltage and current sensed. The design is fully modular. The Routh-Hurwitz criterion is used to determine system stability with the proposed control strategy. To validate the effectiveness and benefits of the proposed configuration and control strategy, simulation and experimental results are provided.

Index Terms: Photovoltaic (PV) power system, three-port converter, dc grid connection, autonomous voltage sharing (TPC).

I. Introduction

Renewable energy sources, such as photovoltaic (PV) energy, are gaining popularity around the world as viable alternatives to address environmental pollution and energy shortages. PV energy sources have proliferated rapidly in recent years and are expected to have the greatest growth on the global power market in the next ten years [1], [2]. The large-scale integration of PV energy into the grid creates challenges in optimising the use of these renewable energy sources. Currently, ac technology is used primarily in distribution systems. Because of their modularity, low device rating, low harmonics, high ac voltage capability, and other advantages, cascaded multilevel converters have been used to connect large-scale PV generation systems to the medium-voltage (MV) ac distribution network. [3]–[5].However, the alternating current grid connection method employs multistage power conversion, which reduces system efficiency. The dc grid is thought to have lower loss, higher transfer capacity, long distance transmission capability, better stability and controllability, easier to supply the dc load, and so on [6]-[9]. Given the dc output nature of PV arrays, an MVDC distribution network with a bus voltage of 10 kV or higher allows for large capacity renewable generation system integration while minimising power conversion losses. Meanwhile, it is simpler to integrate an energy storage system into the dc grid in order to smooth the power flow between renewable energy generation and power consumption and to provide high-quality electric energy. It is possible to improve system stability.All of these benefits make this dc grid connection method appealing for better utilising renewable energy.

The efficient high step-up voltage conversion required to connect PV arrays to the MVDC distribution network is a significant challenge because the output voltages of PV arrays are much lower than the high-voltage (HV) dc bus voltages in the MVDC distribution network. Currently, most research on a dc grid connected PV system focuses on a dc microgrid application with a low-voltage (LV) (1kV) dc bus, with only a few studies on PV connecting to an MVDC distribution network. Differential power processing (DPP) [10–12] and cascaded dc–dc solutions [13–17] are promising candidates for maximum power point tracking (MPPT) of a PV system with a dc output voltage ranging from dozens to hundreds of volts.DPPs only process differential power, which results in a low converter power rating and low power losses. Some DPP distributed control strategies have been proposed [10–12], making the DPP solution advantageous for higher system modularity and well-suited for long submodule strings. DPP solution could be extended to MV application by increasing the number of PV modules. However, because the string PV modules are directly connected to a 10 kV or higher dc bus, high voltage insulation and safety requirements would present difficulties. To achieve proper isolation between PV arrays and the grid, additional isolated converters may be required.

The cascaded dc-dc converters [13]- [17] can potentially be used for the expected application, as shown in Figure 1(a), with the benefits of simple connection, reduced device rating, and modular structure. One of the primary goals of PV systems is to use MPPT to maximise the amount of energy extracted [16], [17]. When the PV arrays' output power is mismatched, unbalanced output voltages for the cascaded dc-dc converters are induced, and the output voltage of a single converter varies over a wide range. Nonisolated dc-dc converters are commonly used in applications that require dozens to hundreds of volts direct current. Meanwhile, because the average voltage stress is low, solving the overvoltage problem will be simple by selecting a higher voltage rating device. It is not suitable for connecting to the MVDC distribution network, however, because the average voltage stress is high and there may be no available devices to meet the peak voltage stress requirement. Meanwhile, because isolation is required, designing an isolated converter with a wide output voltage range increases the design difficulty and system cost. To avoid this problem, voltage limitation control [13] is proposed, which eliminates the need for MPPT. Proposes a cascaded dc-dc and DPP-combined solution to avoid overvoltage and ensure individual MPPT, which could be used for the anticipated application.Proper isolation between PV arrays and the grid can be achieved by using isolated dc-dc converters. The DPP circuits are connected module-to-module to the cascaded dc-dc converters' output ports. The DPP circuits will at least once process the mismatch power among the input PV arrays. When the mismatch power transfers from the first to the last module and is processed n - 1 times, the worst case scenario occurs. Meanwhile, the solution presented in [14] augments the conventional cascaded dc-dc system with additional DPP circuits, cables, and controllers, resulting in a higher circuit count, increased system complexity, and decreased modularity.

Traditional solutions for dc grid-connected PV applications are depicted in Figure 1. (a) A series of DC-DC converters. (b) MMC with two alternating current stages. (c) IPOS-based system.The two-stage dc–dc modular multilevel converter (MMC) technology is shown in Figure 1(b) [18], [19] and is capable of connecting PV arrays to a 10 kV or higher bus voltage. The first-stage dc–dc converter is used for individual MPPT and ensures the isolation between PV arrays and grid. The second-stage half-bridge cells are in a cascaded connection with an output filter inductor to connect to the HV dc bus. The average output voltage of each power unit would vary and differ from others when individual MPPT is realized. Still the same dc-link voltages can be obtained with the duty cycle being varied, as the average output voltage of the half-bridge choppers is D×Vdc_i. The equal voltage stress on every power unit can be obtained. However, when large different MPPs occur, large different duty cycles happen, which will result in large variable voltages being applied to the inductor and then lead to high inductor current stress and conduction losses. Meanwhile, two-stage power conversion is used and system efficiency is hurt. Moreover, the half-bridge choppers share a central controller to ensure the proper phase-shift angle among them to reduce voltage ripples applied to the inductor. The system modularity and scalability are limited. The input-parallel output-series (IPOS) system has been proved to be a promising choice for applications requiring high output voltage with low input voltage [20]– [22]. It can be potentially used to connect PV arrays to the MVDC distribution network. As analyzed in [23] and [24] , the distributed voltage sharing control strategy and the full implementation have been realized for the input-series output-series (ISOS) and ISOP system. However, these distributed control strategies cannot be directly applied to the IPOS system with PV arrays as an input source. Meanwhile, additional dc–dc converters are needed to realize individual MPPT control, as shown in Fig. 1(c), and the cost will be increased. The full system input power is processed twice, which will lower the system efficiency. The main contribution of this paper is to propose a three-port converter (TPC) based system configuration suitable for HV dc grid connected applications, and an autonomous control strategy to achieve coordinate operation of multiple TPCs and distributed PV arrays. It is expected to be a candidate solution to connect PV arrays to the HV dc distribution network, which would have 10 kV or higher bus voltage.

The proposed system is constructed by connecting the input port of each TPC with independent PV arrays, the output ports in series, and the bidirectional ports in parallel to build an LV dc bus. It has the benefits of individual MPPT control, low voltage stress, and the capability to interface with an HV dc bus. Output voltage sharing can be ensured by transferring the mismatch power of input PV arrays through the LV dc bus among TPCs. Only a module's own voltages and currents are sensed for control, and a truly modular design with high system reliability and scalability an be realized.

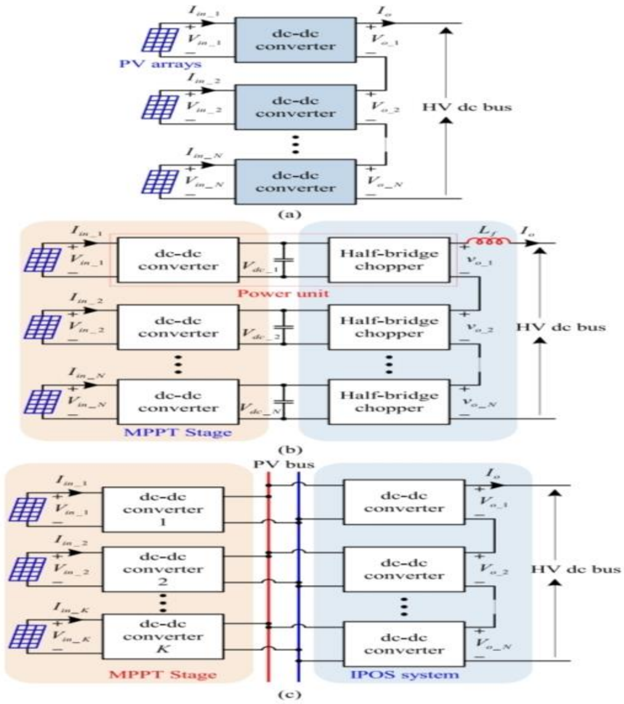


Figure 1: Depicts traditional solutions for dc grid-connected PV applications. (a) DC-DC converters in series. (b) MMC with two stages of alternating current. (c) System based on IPOS.

II. Architecture and Analysis of the System

A. Organization The Proposed TPC-Based System's Description and Analysis

Figure 2 depicts the proposed system configuration based on modular TPCs. Each TPC's input port is linked to a PV energy source, and the output ports of the TPCs in one cluster are linked in series to interface with an HV dc bus. A PV generation system can be connected to the HV dc bus in multiple clusters. These TPCs' bidirectional ports in one cluster are linked in parallel to form an LV dc bus. It should be noted that this dc bus has no load connected to it.Individual MPPT control is possible because each PV array is controlled by a different TPC. The bidirectional port of these TPCs can absorb or supply power to the LV dc bus if it is regulated to enable voltage sharing among these TPCs' output ports. In particular, a TPC with higher PV input power can supply some power to the LV dc bus, and this portion of power can then be fed to the TPC with lower PV input power and transferred to its output port.Thus, regardless of whether the input power from the PV source of each TPC is equal or not, the output power on the output ports of these TPCs can be equal to each other, and output voltage sharing can be achieved simultaneously.

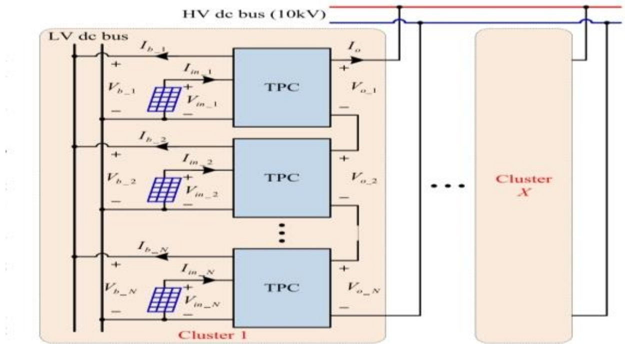


Figure 2: TPC-based distributed dc grid-connected PV generation configuration proposed.

Only additional cables for the LV dc bus are required in comparison to the cascaded dc-dc system. Individual MPPT and voltage sharing can be realised simultaneously with this connection. As a result, balanced voltage stress on these converters is possible. Furthermore, no additional power circuits or controllers are used, which reduces the number of circuits, cost, and system complexity when compared to the solution presented. .Because of the higher power rating of the converters, higher power loss, and higher cost due to the additional cables, the proposed system may not be a good candidate when scaled down to applications with dozens to hundreds of volts dc voltage. However, when used for PV arrays connected to a dc distribution network with a bus voltage of 10 kV or higher, it has some better performance and advantages over conventional ones. Figure 3 depicts the power flow of a two-TPC system to demonstrate the proposed system's operation principle. There is no energy exchange between TPC1 and TPC2 if there is no power mismatch between PV1 and PV2, as shown in Fig. 3(a). In this case, each TPC's input power is delivered directly to its output port, and all PV power is processed only once. If TPC1 has a higher input power than TPC2, as shown in Fig. 3(b), a portion of TPC1's input power is first delivered from the input port of TPC1 to the LV dc bus, and then transferred from TPC2's bidirectional port to its output port. This portion of the power is processed twice, but the rest of TPC1's input power and the entire input power of TPC2 are only processed once. As a result, only the mismatch power between the input PV arrays will be processed twice in the proposed system.

B. Development of the Modular TPC

In the past ten years, numerous TPCs have been proposed. It has been established that an integrated TPC has the benefits of high integration, high power density, low size and weight, and is frequently utilised in renewable energy systems as opposed to a conventional approach with numerous two-port converters. The suggested system can be implemented using any of the TPCs with an isolated output port. The topology shown in [25] is utilised as an example in this study to examine the operation and control of the suggested system, which is based on our prior research. Fig. 4 depicts the modular TPC's topology as well as its main operational waveforms. This TPC's benefits of soft switching, reduced voltage stress on the secondary side switches, decoupled power control, high efficiency, and single-stage power conversion between any two of the three ports have all been independently validated. In the meantime, the primary- and secondary-side voltages [vP and vS displayed in Figure 4(a)] can be well matched with a pulsewidth modulation plus phase-shift (PPS) control method to decrease the peak and rms current values as well as circulation conduction losses.This work does not contain the in-depth study of this TPC, which was completed.

The suggested system may maintain proper isolation between the input PV arrays and grid by using this TPC as the fundamental power unit. The series connection of the output ports enables high step-up voltage conversion. Additionally, the output voltage sharing may be achieved without the usage of additional circuits because of the advantages of TPC, which allow the mismatch power among the input PV arrays to be shared among these TPCs through the LV dc bus.

By employing this TPC as the primary power unit, the suggested system might be able to maintain adequate isolation between the input PV arrays and grid. High step-up voltage conversion is made possible by the output ports' series connection.

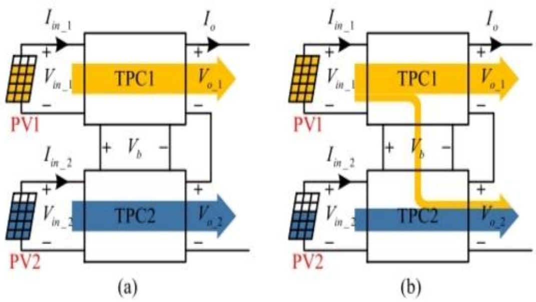


Figure 3: A two-TPC system's power flow study. Without mismatch power, in (a). (b) With power mismatch.

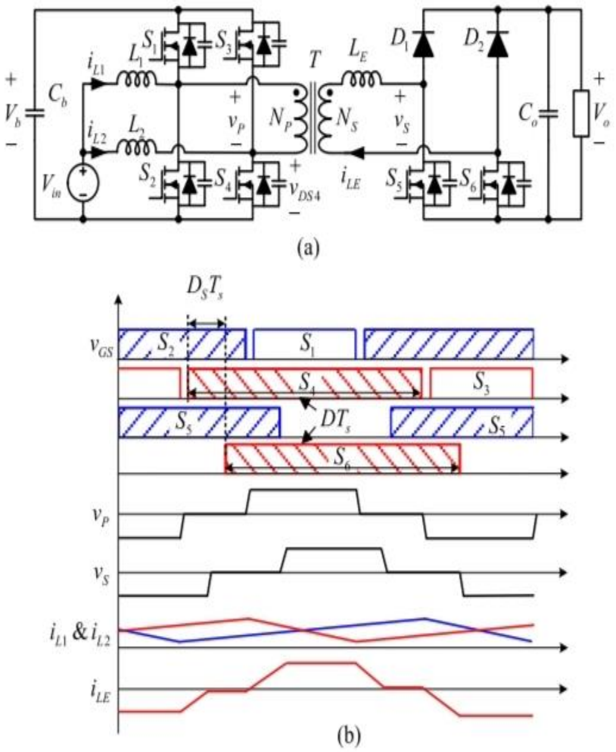


Figure 4: Realization of the modular TPC, (A) The TPC's topology. (b) Significant operational waveforms

The benefits of TPC allow the mismatch power among the input PV arrays to be shared among these TPCs through the LV dc bus, which enables the output voltage sharing to be accomplished without the necessity of extra circuits. As a result, it is feasible to develop compact systems and high system integration. We decide on TPC as the main power source for the recommended system because of these advantages.Figure 5: Shows the control block for each TPC in the suggested system operating with MPPT.

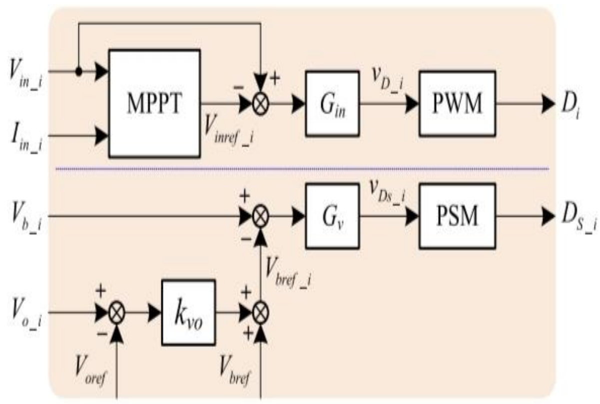


Figure 5: The suggested system's control block in constant-power operation

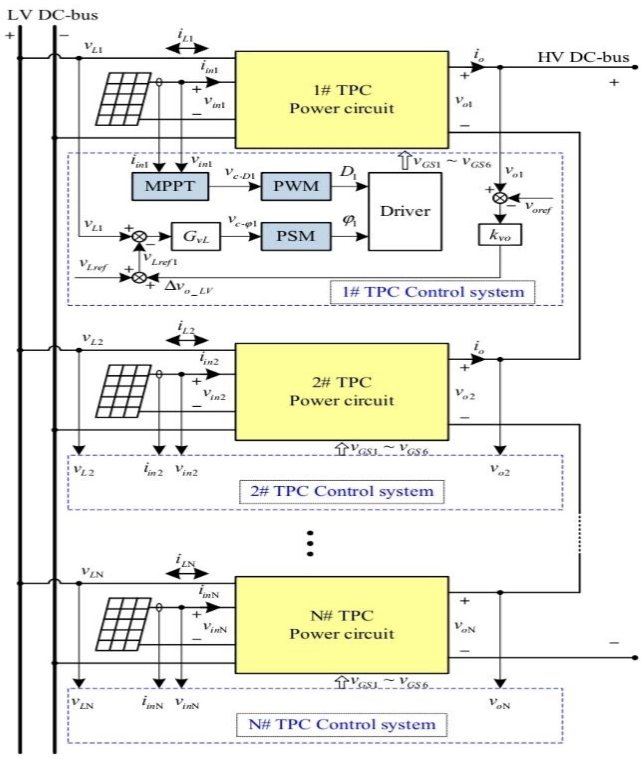


Figure 6: A proposed system for use in real applications that includes bypass diodes.Figure 8 shows a diagram of a TPC-based modular PV system.

III. PROPOSED STRATEGY FOR CONTROL

A. System Control Strategy

1. Operation of the MPPT: To provide management of both the individual MPPT and the output voltage sharing, a unique control technique is suggested for the TPC-based system. Figure 5 depicts the control block of a single TPC. Individual MPPT control is made possible by sensing and using the input voltage and current. The voltage reference of the TPC's bidirectional port is adjusted using the difference between the output voltage and its reference, which is determined as

$$V_{bref\_i} = V_{bref} + K_{vo}(V_{o\_i} - V_{oref}), K_{vo} > 0, i = 1 \sim N \quad (1)$$

where Vbref I is the ith TPC's output voltage, Voref is the output voltage voltage reference, kv o is the coefficient, and is greater than zero, Vbref I is the ith TPC's new bidirectional port voltage reference, Vbref is the initial value of the bidirectional port voltage reference, N is the number of TPCs used in the system.

The TPC with the bigger input power will have higher output voltage, assuming no mismatch power is passed across the LV dc bus and the proposed system is operated exactly like the cascaded dc-dc system. This TPC's bidirectional port voltage will be managed at a greater level in accordance with (1), and more power will be output to the LV dc bus. Less power is therefore sent to its output port as a result. The TPC with the lower input power will use more of its bidirectional port to absorb power and more of its output port to send power. As a result, the imbalanced output voltages are decreased, and all TPCs will finally function at steady state with the same output voltage.According to the analysis mentioned above, if a perturbation causes Vo I to rise and Vo j to fall, the ith TPC's bidirectional port voltage reference will rise and the jth TPC's voltage reference will fall, reducing the voltage difference between Vo I and Vo j, and the operating points of these two TPCs will return to the same steady-state point. Only the TPC's own voltages and currents are detected to implement individual MPPT control, bidirectional port voltage regulation, and output voltage sharing control, as shown by the control block in Figure 5. A single module and system can function properly using only their own circuits and sensors; an external master controller is not required for control.All TPCs in the proposed system can have their regulators (Gin and Gv), coefficient kv o, starting voltage reference of the bidirectional port (Vbref), output voltage reference (Voref), and initial voltage reference (Vbref) adjusted by the local controllers and be the same. As a result, it is possible to realise a genuinely modular design with great system stability and scalability.

All TPCs have their output voltage re

$$V_{oref} = \frac{V_{dc\_n}}{N} \quad (2)$$

ference set at

where Vdc n represents the HV dc bus' nominal voltage. 0 volts is the starting voltage reference for the bidirectional p

$$V_{bref} = \frac{V_{oref}}{n} = \frac{1}{n} \cdot \frac{V_{dc\_n}}{N} \quad (3)$$

ort.

where n is the transformer's turns ratio in the modular TPC, defined as n = NS /NP, where NP and NS are the main and secondary windings' individual turn numbers.

Table I, where Vdc is the voltage of the HV dc bus and Davg is the average value of the duty cycles of the half-bridge choppers, summarises the performance comparisons between the suggested method and conventional methods. In contrast to typical systems, the suggested system architecture and control technique has some advantages, including individual MPPT, output voltage sharing performance, no additional circuits needed, only mismatch power being handled twice, and totally modular implementation. Table I shows that the suggested system uses fewer circuits and achieves excellent integration, which leads to a smaller system size.

2. Constant-Power Operation: In order to minimise overload issues when too much power is generated under MPPT operation, it is important to operate the grid-connected PV system with constantpower control [28]. Fig. 6 depicts the proposed system's control block in constant-power operation. The supervisory computer provides the power reference, which is specified as

$$P_{\mathrm{ref}} = \frac{P_{\mathrm{ref\_}G}}{N} + \frac{P_{\mathrm{ref\_}G} - P_o}{N} \qquad (4)$$

where Po is the total output power and Pref G is the TPC-based PV system's total power reference.

To be clear, the supervisory computer will be required to keep track of the system's operational state and transmit command signals to make sure the grid-connected PV system is operating properly. The supervisor, which is present in both MPPT and constant power operation modes, is necessary for all practicable systems, but not specifically for the proposed system. Only low-speed communication is used to communicate all information regarding the state of the system's operation and its directives between the supervisor and local controllers. The control for constant-power operation is not strictly modular because the power reference is received from the central supervisor, and this is true for other potential solutions as well.The autonomous output sharing performance can still be guaranteed with their individual circuits and sensors since only the MPPT block in Fig. 5 is replaced for constant-power control.

3. Special Working Conditions:

a. Failure of PV Energy Source: The suggested system can continue to run reliably even in the event that some PV Energy Sources fail. This is made possible by the mismatch power processing capability. Consider a two-TPC system and suppose PV2 is not connected to the system. In other words, the TPC2's input port won't receive any power. A portion of the input power from PV1 will be transferred to the bidirectional port of TPC2 and subsequently be sent to the output port, per the power-flow channels depicted in Fig. 3(b). As a result, even if the PV energy source fails, the output voltage sharing performance may still be guaranteed, and no overvoltage issues will be brought about.

b. System connection or disconnection of the module:

The antiparalleled bypass diodes are required and attached to the output ports of these TPCs in order to preserve correct functioning when some modules are disconnected from the system, as shown in Figure 7. Module joining or leaving the system. Otherwise, there would be a high-side power interruption. Switches Sb I and So I are switched OFF to detach the malfunctioning TPC from the system in the event that the ith TPC fails. This forces the output current to commutate and flow naturally through the bypass diode.To ensure that the system operates properly and that there is no power interruption, the remaining TPCs will keep providing power to the HV dc bus. However, the PV system does occasionally experience a sharp loss in power, which could result in a drop in the dc bus voltage. Switches Sb I and So I are turned ON when the ith TPC is prepared to connect to the system, and voltage Vo I will be applied to the bypass diode to force it OFF. The energy storage system, which is also connected to the HV dc bus, can smooth out the resulting power fluctuation and limit the negative effects of the PV system's intermittent nature.

In fact, the number of the modules changes depending on whether certain TPCs are connected to or disconnected from the system. It is still possible to retain output voltage sharing, individual MPPT control, and good system operation. It is possible to obtain good system redundancy and scalability. The output voltages and bidirectional port voltages of some TPCs will change depending on whether they are attached or detached from the system. The increased or decreased voltage stress will be relatively minor if N is large enough, which will have little effect on the modular TPCs' design.

To reduce the inrush current when connected to live buses, the appropriate start-up control is required. For instance, precharging all TPCs' output capacitors and gradually raising the power reference are potential fixes. We can refer to several start-up control techniques for MMCs connected to HVDC [29], [30] in our future research. However, a thorough research is not presented because this issue is not the primary topic of the work.

B. Analysis of Output Voltage Sharing Errors:

Based on the previous analysis and (1), it can be deduced that if all TPCs use the same voltage references, Voref and Vbref, and the coefficient kv o, the ideal output voltage sharing performance may be achieved. In reality, it is challenging to have the same qualities in every module. We can get the following from (1) assuming that the voltage references and coefficients of the ith and jth TPCs differ:

$$\begin{cases} V_{b\_i} = V_{\mathrm{bref\_}i0} + k_{vo\_i}\left(V_{o\_i} - V_{\mathrm{oref\_}i}\right) \\ V_{b\_j} = V_{\mathrm{bref\_}j0} + k_{vo\_j}\left(V_{o\_j} - V_{\mathrm{oref\_}j}\right) \end{cases} \qquad (5)$$

Voref I and Voref j are the output voltage references, kv o I and kv o j are the coefficients, and Vbref i0 and Vbref j0 are the starting bidirectional port voltage references of the ith and jth TPC, respectively. Vb I = Vb j = Vb is substituted into (5) to produce

$$V_{o\_i} - V_{o\_j} = (V_{\text{oref}\_i} - V_{\text{oref}\_j}) + \frac{k_{vo\_j} - k_{vo\_i}}{k_{vo\_i}k_{vo\_j}}V_b + \frac{k_{vo\_i}V_{\text{bref}\_j0} - k_{vo\_j}V_{\text{bref}\_i0}}{k_{vo\_i}k_{vo\_j}}. \quad (6)$$

We see from equation (6) that the output voltage sharing is more accurate the smaller the difference between the voltage references or coefficients. The voltage sharing error is decreased as a result of the bigger kv_I and kv_j. But in accordance with (1), as kvo rises, the voltage error between the regulated bidirectional port voltage and the nominal value Vbref will also rise. As a result, the effectiveness of voltage regulation for bidirectional ports will be affected.

Therefore, the proposed voltage-sharing control methodology is comparable to the droop method, and the coefficient kv o has a similar role to the droop coefficient in the droop-control strategy, which has been widely utilised for parallel-connected dc-dc converters or dc-ac inverters [31]–[33]. In droop control, the output current of the module itself is monitored in order to modify the output voltage reference and implement load-current sharing. In order to achieve voltage sharing using the suggested control approach, the module's own output voltage is added to the controller. These two control strategies don't use current- or voltage-sharing buses, which results in a more reliable system and good system flexibility. But this will affect how well both devices regulate voltage.To process the power mismatch among the input PV energy sources, the suggested system just connects the bidirectional ports as the LV dc bus. Error removal [32] and very precise bidirectional port voltages are not requirements.

C. Analysis of System Stability Using Proposed Control Strategy:

This section examines the stability of the suggested system with the suggested control scheme. The voltage gain G = 1 and continuous conduction mode (CCM) output power of the modular TPC can be calculated as

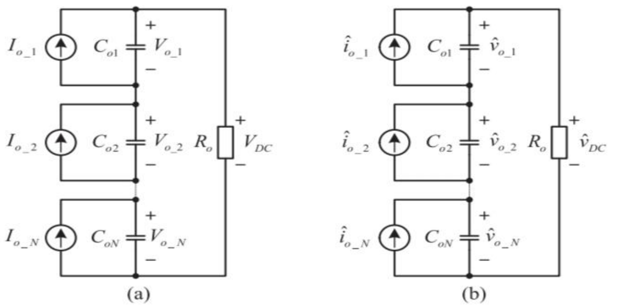
$$P_o = \frac{nv_b v_o\left(40D + 22D_S - 20DD_S - 28D^2 - 10D_S^2 - 13\right)}{36f_s L_E} \quad (7)$$

where !

$$G = \frac{V_o}{nV_b}. \quad (8)$$

of switches S2 and S5, D is the duty cycle of the driving signals of ... ıtio given as DS = S /. The voltage gain G is defined as

In Fig. 8 [34], a current source based equivalent model of the suggested system with N TPCs is presented. The steady-state output current of the TPC may be calculated as



$$I_o = \frac{nV_b\left(40D + 22D_S - 20DD_S - 28D^2 - 10D_S^2 - 13\right)}{36f_s L_E}. \quad (9)$$

Figure 7: Equivalent circuit of the suggested system Large signal model is (a). Small signal model, (b). Small changes to DS and Vb have given us

$$\hat{i}_{o\_i} = \frac{n\left(40D_i + 22D_{S\_i} - 20D_iD_{S\_i} - 28D_i^2 - 10D_{S\_i}^2 - 13\right)}{36f_s L_E}\hat{v}_{b\_i} + \frac{nV_{b\_i}\left(22 - 20D_i - 20D_{S\_i}\right)}{36f_s L_E}\hat{d}_{S\_i}. \quad (10)$$

The relationships shown in Fig. 8 may be calculated, where Ro is the load resistance:

According to Fig. 5, we obtain

where Hvo is the output voltage sensor gain, Hvb is the bidirectional port voltage sensor gain, and Gv is the compensator's gain.

$$D_{S\_i} = \left[V_{b\_i}H_{vb} - \left(V_{o\_i}H_{vo} - V_{\text{oref}}\right)k_{vo} + V_{\text{bref}}\right]G_v \quad (12)$$

Therefore, it is possible to obtain the perturbations of the phase-shift ratios as

Substituting Vb i = Vb into (1) and assuming the same characteristics, we obtain the following relation:

$$NV_b = NV_{\mathrm{bref}} + k_{vo}\left(V_{\mathrm{dc}} - NV_{\mathrm{oref}}\right). \quad (14)$$

Assuming a fast voltage controller, we ha v

$\hat{d}_S$

$$\begin{cases} A_i = \frac{n\left(40D_i + 22D_{S,i} - 20D_i D_{S,i} - 28D_i^2 - 10D_{S,i}^2 - 13\right)}{36 f_s L_E} \\ B_i = \frac{n V_{b,i}\left(22 - 20D_i - 20D_{S,i}\right)}{36 f_s L_E}. \end{cases} \quad (17)$$

$$NV_b = k_{vo} v_{\mathrm{dc}}. \quad (15)$$

Combining (10), (11), (13), and (15)

$$\frac{\hat{v}_{o\_j} - \hat{v}_{o\_k}}{\hat{v}_{\mathrm{dc}}} = \frac{A_j k_{vo} R + B_j G_v H_{vb} k_{vo} R - N}{NR\left(sC_{oj} + B_j G_v H_{vo} k_{vo}\right)} - \frac{A_k k_{vo} R + B_k G_v H_{vb} k_{vo} R - N}{NR\left(sC_{ok} + B_k G_v H_{vo} k_{vo}\right)} \quad (16)$$

yields where Ai and Bi are defined as

D. Verification of a 10 kV PV System Using Simulation

The effectiveness and benefits of the suggested system with its control method have initially been tested using a 10-kV PV system that has been modelled and simulated in Simulink. Table III provides a list of the essential circuit parameters. The specific design factors for a single TPC have been examined], hence they are not included here. The entire modularity has been guaranteed in simulation, and only the module's own voltages and currents are detected for control.

Figure 11 displays the simulation results of the suggested system and its control technique. As demonstrated in Figure 11(a), the unbalanced input power has caused significant output voltage imbalances prior to time zero. The output voltage sharing is accomplished when the suggested control method is used at time t0 by distributing the mismatch power among the input PV sources via the LV dc bus. In the case of step input power, it can be shown from Figure 11(b) that satisfactory output-sharing performance has been guaranteed both in the steady state and under transient situations. Figure 11 displays the simulation results for the scenario when TPC2 and TPC3's input sources are both detached from and attached to the system (c). No electricity enters these two TPCs' input ports when their input sources are cut off. Even so, all TPCs are guaranteed to have adequate output voltage sharing, both in steady-state and transient circumstances. The system continues to run well, which shows that it has a good fault-tolerant capability. The simulated outcomes for disconnecting and reconnecting TPC2 and TPC3 from the system are shown in Figure 11(d). TPC2 and TPC3 are cut off from the system at time t1. It is discovered that the power interruption did not occur and that the other TPCs are still supplying power to the HV dc bus. The remaining TPCs continue to share the output voltage, and by increasing their output voltages, they adequately meet the theoretical analysis. TPC2 and TPC3 are joined to the system at time t2. The output voltage of each TPC is lowered while good voltage sharing is accomplished. According to Fig. 11(d), even if certain TPCs are attached or detached from the system, the system will continue to function correctly and exhibit good voltage-sharing performance. This makes it possible to have good system redundancy and scalability.

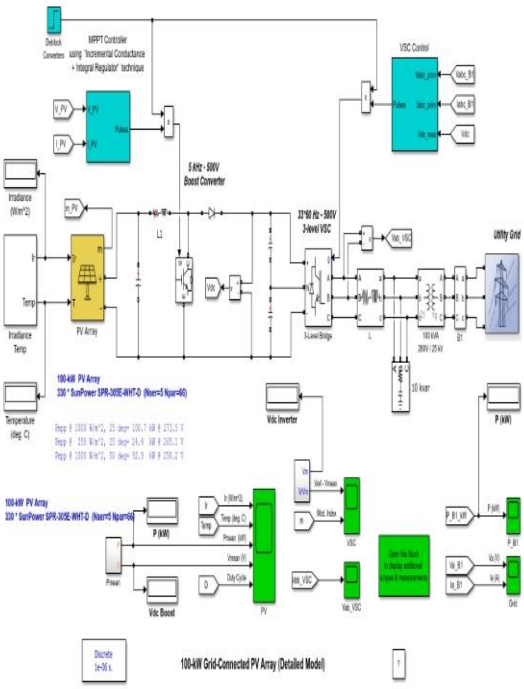


Figure 9: Simulation of A Distributed DC Grid-Connected PV System with Autonomous Output Voltage-Sharing Control Based on Three Converters

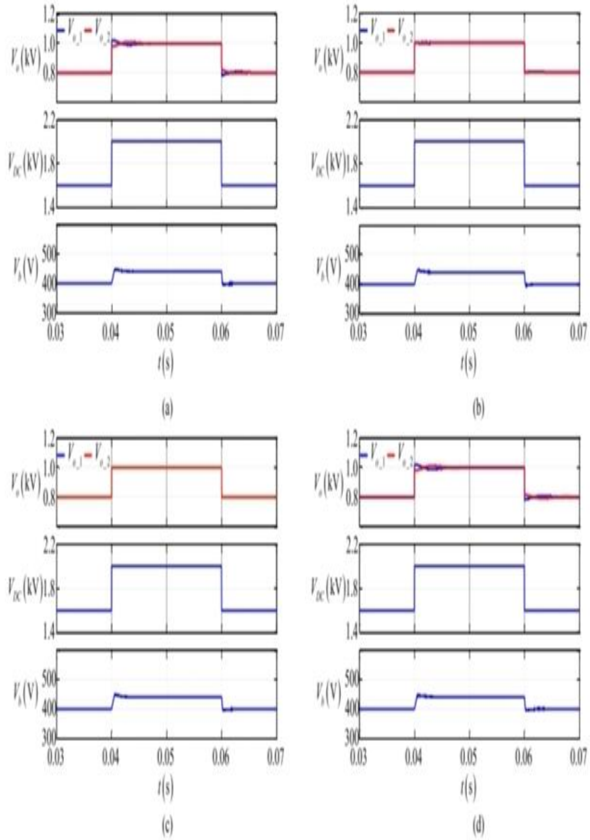


Figure 10 shows the simulation results for the situation of component mismatch with stepped output voltage variations. Co 1 = 470 F and Co 2 = 570 F, respectively, are two different output filter capacitances (a). (b) A transformer with a different turns ratio (n1 = 2, n2 = 2.2). (c) Differing inductances for energy transmission (LE 1 = 35 H, LE 2 = 40 H). (d) Variable transformer turns ratio, energy transfer inductance, and output filter capacitance (Co 1 = 470 F, Co 2 = 570 F, n1 = 2, n2 = 2.2, LE 1 = 35 H, LE 2 = 40 H).

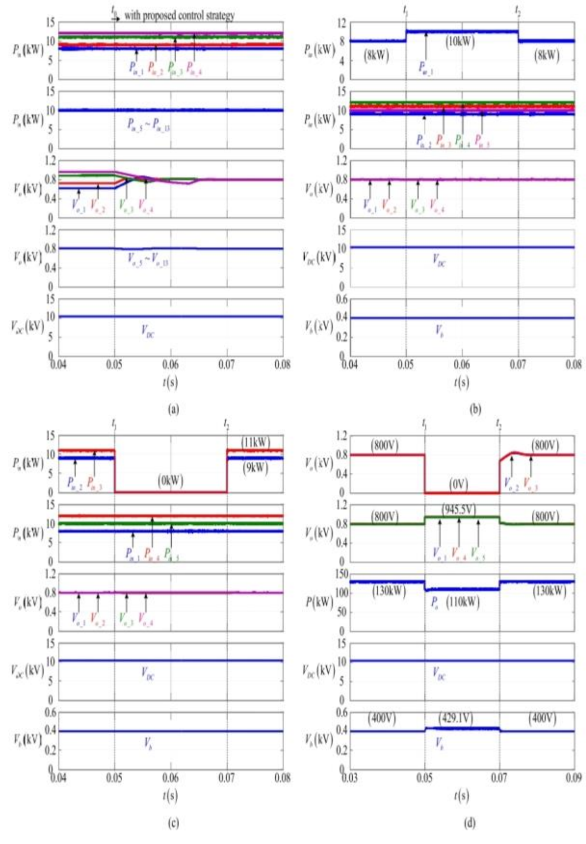


Figure 11: Results of the simulation (a) Without or including the suggested control approach. (b) Step input power case. (c) The situation in which the input source is either connected to or detached from the system. (d) A situation where TPC1 was either linked to or unplugged from the system.

IV. CONCLUSIONS

This paper proposes and investigates a novel TPC-based system configuration and its control strategy for a distributed dc grid-connected PV application. The proposed system is composed of multiple modular TPCs and is generated by connecting each TPC's input port to an independent PV energy source, the output ports in series to interface with an HV dc bus, and the bidirectional ports in parallel to form an LV dc bus. Individual MPPT, low voltage stress, and HV output are all accomplished. Autonomous output voltage sharing has been realised both in the steady state and during dynamic progress by controlling the bidirectional port voltage in a linear relationship with the output voltage.All TPCs use the same power stage and distributed controller, which simplifies design and improves system modularity, reliability, and scalability. The detailed presentation of system configuration, operational principles, voltage-sharing characteristics, and system stability. The analysis and performance have been thoroughly tested. The proposed TPC-based system, with its control strategy, is an excellent candidate for dc grid-connected PV applications, according to analysis and simulated and experimental results.

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