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Topology and Control of Transformerless High Voltage Grid-connected PV System Based on Cascade Step-up Structure

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Abstract— **In order to realize maximum power output of photovoltaics (PV), reduce line losses, and decrease abandoned solar energy during weak irradiance , a new medium voltage grid-connected PV system structure based on cascaded converters was proposed in this paper. A transformerless cascade step-up structure, instead of applying line-frequency step-up transformer, is proposed to connect PV directly to the 10 kV medium voltage grid. This series-connected step-up PV system integrates with multiple functions, including separated maximum power point tracking (MPPT), centralized energy storage, power quality regulation. Its inherent excellent features makes it not only adapt to different geographical and environmental installing conditions, but also to improve converter efficiency and flexibility. This paper focuses on the analyses of system structure design, control principle and strategy, and then comparing the performance of different PV plant structures, including central, multi-string and this novel series-connected structure. Additionally,, by properly choosing storage battery capacity in accordance with the demand of power grid and load, this structure is able to achieve short-term power grid support and peak-load shifting.**

Keywords— transformerless PV system; cascade step-up; balance controller; energy storage; three-phase complementary balanced

I INTRODUCTION

Power electronics converters are used to carry out the required conversion from DC power produced by photovoltaic (PV) modules to an AC form that suits the voltage and current in the grid power lines. Nowadays, most of the commercial and utility-scale solar projects in the world have traditionally employed central inverters or string inverters [1]. When using a central inverter, the DC power produced from each PV string transfers through cables to combiner boxes where all the strings connected in parallel. Afterwards, the DC power is converted to AC by the central grid-connected inverter. However, when using string inverters, there are multiple low-power inverters for several strings, so the DC power from a few strings transmits directly to a string inverter rather than a combiner box. Based on the basic principle of those two structures i.e. PV strings works parallel in an direct or indirect configuration, it results in that voltage is limited in a low level (≤1000V) and thereby current becomes large, so that power equipment suffers from great losses, lots of confluence devices, power cable and inverters, and then cause a large power loss, especially under weak irradiance [2]. Moreover, due to distributed PV arraies which have different parameter, accurately tracking the maximum power point of the PV cluster cannot be realized automatically in centralization type applications, leading to power generation loss. The configuration based on string inverters makes perforemace prior to central grid-connected inverter based structure. But the string inverter-based configuration has too many grid-connected points, which can easily lead to system oscillation and eventually, the inverters cut off form the grid. In particular when the PV generation system locates at the terminal of a large power grid, a weak power grid or away from load, this unstable phenomenon becomes even more serious [3].

There are many advantages in series-connected PV systems, such as accurately maximum power point tracking (MPPT), upgrading the output voltage level and improving the energy utilization of PV arrays in low irradiance, reducing loss of power cables and transformers, reducing volume of converter devices, and also realizing energy optimization and static var generator (SVG) functions. In order to realize these advantages, a novel structure without line-frequency step-up transformers is proposed and designed in this paper. On the other hand, the transformerless PV inverters have the advantages such as low cost, small size, light weight and high efficiency [4]-[6]. There are three sub-circuits in whole system that corresponding to phase A, B, and C, and each sub-circuit consists of a cascade PV converter unit. Therefore, a three-phase grid-connected system consists of three branches with star or delta connection [7] - [9].

The transformerless high-voltage PV system includes three paralleled single-phase AC power generation units with 120° phase shift and one common energy storage unit. Because they are assembled by a star or delta type, it can be named after star or delta three-phase cascade high-voltage grid-connected PV system respectively. This new structure is one of the transformeless high voltage grid-connected PV system, which can not only improve the output voltage to 10kV and thereby reduce output current and decrease cable cost, but also break the

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entire system down into parts that lead to reduce or elimate cable length, power container, and line transformers. It is better to use DC/AC inverter to keep PV strings insulated from the grid, implement maximum power tracking, guarantee maximum electric generation output, elimate combiner box, reduce DC cable, greatly reduce risks of DC electrical arcing, and then increase system safety [10] - [13].

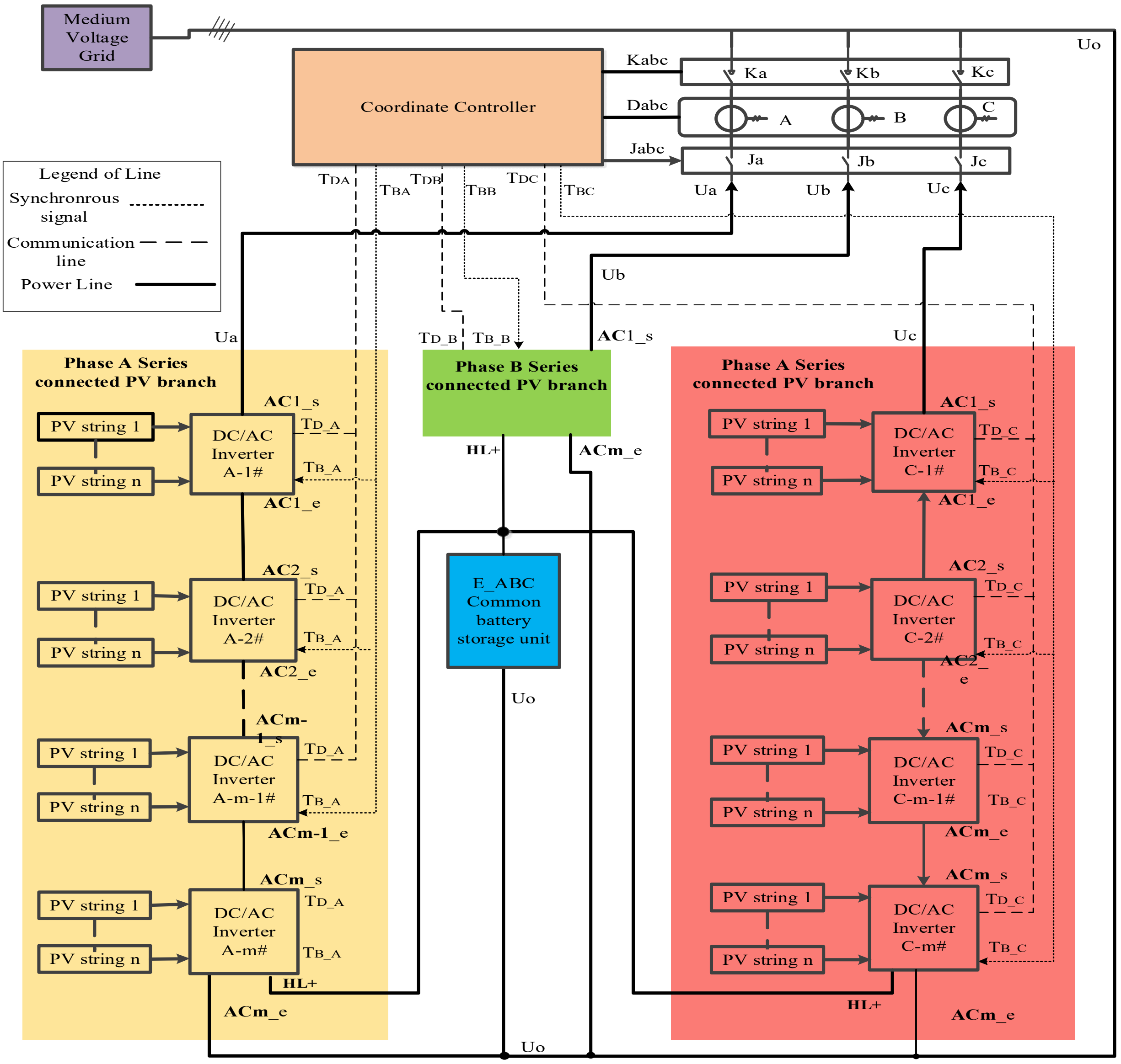
Moreover, PV power generation is assisted further by energy storage, to ensure system three-phase balanced output, support the active and reactive power of the grid, retrain flickers and fluctuations, thus making PV power generation high proportion access to power grid possible.

The structures of the cascade star and delta three-phase PV system are introduced in Section II. The working principle of converter, unit and system is presented in Section III. In Section IV, performance comparison between central, string and cascade structre is provided, and the proposed cascade structure has many advateges than others.

II DESIGN OF CASCADE STRUCTURE

A. Structure of star and delta three-phase complementary balanced series-connected PV station system

In PV systems, in order to realize balanced three-phase complementation for the utility grid, it should use single-phase converters to form a three-phase converter and then regulate their output power separately. There are two types of connection in three-phase system i.e. star connection and delta connection. Each cascaded high-voltage PV system is composed of three



Notes: The symbols identified in Fig. 1 and 2 are: TDx, TD_x and TBx, TB_x indicates data communication signal and synchronous bus signal between coordinate controller and DC/AC inverter (x indicates phase A, B and C); ACm_s, and ACm_e indicates power terminal start and power terminal end of DC/AC inverter; HL+ is port of the NO.m DC/AC inverter which connected to the common energy storage battery bank.

Fig.1 Star type block diagram of series-connected high-voltage PV station system with three-phase complementary balanced single-phase series-connected branches, one common battery storage unit and one coordinate controller unit. As an example the star connection based system structure is shown in Fig.1.

In Fig. 1, the high-voltage PV station consists of three single-phase cascaded PV power generation units of phase A, B and C, the common battery storage unit E_ABC and the coordinate controller. These three single-phase cascaded PV power generation units are connected in a star manner, and their common points are connected with E_ABC. The output terminal of the three-phase high-voltage PV station is connected with coordinate controller's input *Ua, Ub, Uc*, and the output of controller is connected with three-phase medium voltage grid.

B. *Structure of single-phase cascade power generation unit*

In the single-phase cascaded PV power generation unit, the output terminal end of the first high-voltage isolated DC/AC inverter is connected with the second one's output head end, and then the output terminal end of the second one is connected with the third one's output head end, and so on. For the m-th DC/AC inverter, its output terminal is the last output of the single-phase cascade PV power generation unit, and therefore the output voltage of the entire single-phase connenction is,

$$U_{acs}=\sum_{m}^{1}u_{ac}(m) \tag{1}$$

Because the PV string's rated voltage is usually lower than 1000V, if too many PV strings are connected in series, the high voltage will damage PV strings. It is necessery to add a high-voltage isolation transfromer between the PV DC/AC converter and HVAC bus to enhance isolation of the PV system. When each PV string is isolated from the high-voltage bus by the DC/AC power conversion stage with transformers, it is easy to realize every PV DC/AC converter's withstand voltage equal to the system voltage U_{acsmax}, so *m* DC/AC power converters can be connected in series.

$$\begin{cases} U_{as}=\sum_{m}^{1}U_{a}(m) \\ U_{bs}=\sum_{m}^{1}U_{b}(m) \\ U_{cs}=\sum_{m}^{1}U_{c}(m) \end{cases} \tag{2}$$

C. *Structure of high-voltage isolated DC/AC inverter*

The single-phase cascaded PV power generation unit consists of number of high-voltage isolated DC/AC power converters. The DC/AC power converter is composed of two or more maximum power point tracking (MPPT) modules, a DC/AC H-bridge power converter module, a controller module, a electric source module and a HVAC isolation module. The input end of the high-voltage isolated DC/AC power converter is connected with PV string's output end. In particular, the last HVAC converteres in phase A, B and C are equipped a DC/DC battery converter that connects with E_ABC i.e. the common battery storage unit.

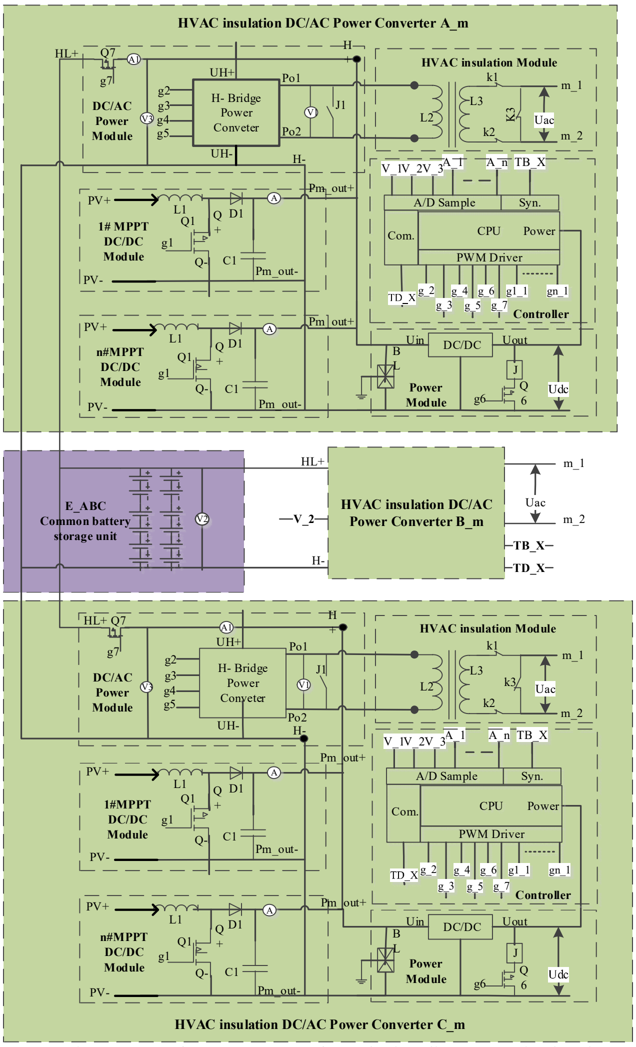


Fig.2 star DC/AC power transform device diagrammatic sketch

As shown in Fig. 2, the output end of PV string is connected with input end of a MPPT DC/DC module, and this MPPT module is a Boost-type converter for accurately tracking PV power. All the outputs of the *n* MPPT modules are in parallel, then the output ports of the MPPT modules are connected in parallel with the input port of the H-bridge power converter module in the DC bus. The DC/AC transform module's output end is connected with the input of AC transformer. The output of isolation modules is cascaded with the output of other DC/AC power converters. For the last converter, the DC/DC module is connected with common battery storage unit by a extra DC/DC converter.

The converter controller consists of an A/D sample unit, a synchronorous unit, a connunication unit, a PWM driver unit and a CPU unit.The input of auxiliary power supplies which are for all controller and drive module is connected with the DC bus.

Ⅲ WORKING PRINCIPLE

A. *Principle of three-phase balance*

In a real project, there are differences between various PV strings in terms of PV parameters, radiance and shading, number of panels in a PV array, environmental diversity of PV array location. These inherent differences make the output voltage $U_a(m)$, $U_b(m)$ and $U_c(m)$ of each DC/AC power converter are possibly different. In order to make sure output power of star-connected cascade PV system keeps three-phase power balanced, which means $P_a = P_b = P_c$, as expressed in (3). In a series-connected branch, the current is same, i.e. $I_{as} = I_{bs} = I_{cs}$, so it is necessery to keep $U_{as} = U_{bs} = U_{cs} = Uacs$, where $Uacs$ is the utility grid voltage. The controller must coordinate every DC/AC power converter by controlling the output voltage of each converter.

$$\begin{cases} P_a = \sum_{m}^{1} U_a(m) \times I_{as} \\ P_b = \sum_{m}^{1} U_b(m) \times I_{bs} \\ P_{cs} = \sum_{m}^{1} U_c(m) \times I_{cs} \end{cases} \tag{3}$$

where I_{as}, I_{bs}, and I_{cs} are star three-phase alternating series-connected PV array output current; P_a, P_b, and P_c represent output power of each phase's PV arrays.

B. Principle of converter initial start

1) Very low irradiation condition

When irradiation is very low or does not exist at all, there is no power supplying to DC/AC power conversion devices, due to the switch of protective relay is closed, and therefore the input internal resistance of the transformer is zero. According to transformer theory, the output impedance is expressed as $R=B^2r\ \Omega$, where B is the transformer ratio, r is the internal resistance of alternating isolation output module, so the output impedance $R=0\ \Omega$, and there is no power output.

2) Low irradiation condition

When the irradiation gradually increases, the input power of the PV converter increases accordingly. After the einput voltage reaches the DC/DC starting voltage, the auxiliary power supply starts to work, and then the controller starts to work. The m-th DC/AC converter controller will check whether the voltage of common storage batteries reaches the setting voltage. If the batteries' voltage is lower than the DC bus voltage, the PV strings will start to charge the batteries until the charging current is close to zero. Afterwards, the DC/AC converter shift to the next working status.

C. Operation principle of the cascade system

1) Operation mode in low irradiation

Low irradiation makes the PV array cannot support cascaded high-voltage PV station to inject enough power to the grid. This system has one advantage that can avoid wasting solar energy by storing it into the common battery bank. The central controller coordinates each phase of generation units to charge the battery bank through m-th DC/AC power converter as shown in Fig.3.

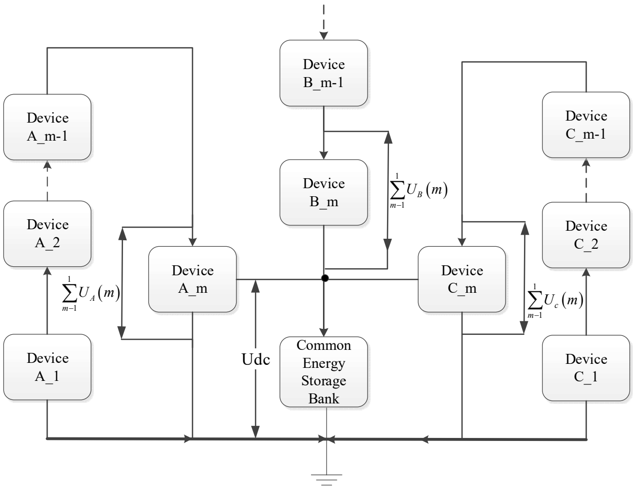


Fig. 3 Diagram of grid-disconnected operation in low irradiation.

Star-connected coordinate controller is in charge of establishing the synchronization and communication signal for every DC/AC converter in each phase of cascaded PV power generation units, and then send synchronous signals and interactive data in real time. At the same time, it also counts the quantity of working converter in every cascade unit. Until the number of the working DC/AC power conveters in the cacade branch is more than the minimum number M_{min}, and M_{min} refers to (4), the coordinate controller asks all DC/AC converter to output high resistance. Then, the AC contact is controlled to be closed from an open state, and the star-connected three-phase cascade high-voltage PV station is connected to the grid.

$$M_{min} = U_{acs}/U_{mmax} \tag{4}$$

where M_{min} is the minimum number of DC/AC converters, $Uacs$ is the utility grid voltage, U_{mmax} is the maximum output voltage of DC/AC converters.

The coordinate controller collects and processes the infromation from every converter, including voltage amplitude, phase, and frequency, and then sends the control data and synchronous pulse signal to DC/AC converters. These converters receive the basic command and synchronous signal, and drive the power circuit module to output AC power to the isolated transformers. After this mode, the PV system goes into a normal operation mode.

2) Normal operation mode

The PV converter contoller collects each current of MPPT module and voltage on the DC bus by the A/D sample circuit, and according to the MPPT strategy, drives the H-bridge power bridge to achieve maximum PV power output. The m-th converter's contoller also collects the current and voltage of the battery bank. All the infromation is sent to the coordinate controller by a bi-directional communication network, for instance optical fibers or wireless nets. After the data is uploaded to the coordinate controller, frequency and voltage analysis, calculation for compensations of power factors and three-phase equilibrium and synchronous control signal will be processed in the CPU of the controllers. The caculation result will be sent back to each controller of DC/AC power converter.

The irregular block of the cloud causes the output power of the PV string to be different. This results in the output power of each DC / AC converter in the cascade high-voltage PV power plant different. The controller sums the output power of each PV power plant to obtain the total power of each phase cascade PV power unit, and then add the capacity of the battery bank, ultimately calculates the output current of the star three-phase cascade PV power plant. Based on the output current and output of every PV string, it is easy calculate the voltage reference for every converter.

D. Operation mode in short-circuiting

The short-circuiting switch k3 as shown in Fig. 2 keeps open when the system operates normally. Once there are some DC/AC power converters need to be maintained or changed, in order to avoid disturbing other converters in the same cascade unit, the short-circuiting switch can conduct, and thereby the converter disconnects quickly from its cascade unit. The fault information will be sent to the coordinate controller.

Ⅳ PERFORMANCE COMPARISON

A case study of 10MWp/10kV grid connected PV power station carries out to compare centralized structure, string structure and cascade structure in terms of performance and economy. By comparing different aspects, the proposed cascade scheme is valid, specifically, to reduce AC current, save cost, improve the efficiency of power generation in weak irradiation and the accuracy of PV maximum power point tracking, and the results are listed in Table I.

TABLE I
COMPARISON BETWEEN CENTRALIZED, STRING AND CASCADE SYSTEM

Item	Centralize	String	Cascade
Confluence device (quantity)	>200	>100	0
DC/AC converter	0	0	333*30kW
Confluence power cable (km)	>100	>100	0
Current (kA)	20	20	1
Energy storage	No	No	Yes
Switch cabinet (quantity)	>50	>50	0
Inverter	20*500kW	333*30kW	0
Step up transformer	1*10MW	10*1MW	0
AC power cable loss	high	high	low
Transmission distance	near	near	far
MPPT range	narrow	narrow	wide
Efficiency in weak irradiation	low	high	high
Cooling mode	force	natural	natural
Fault redundancy	low	high	high

By comparing these three PV station configurations, the major advantages of applying the proposed cascade structure are as follows:

1)Absence of a large number of convergence devices avoids failure and malfunction caused by a large number of fuses, circuit breakers, and improved the reliability.

2)Series-connected PV power station improves the AC output voltage and thereby reduces the transmission current, reduces the power loss of the cable and equipment, and at the same time reduces the failures caused by the DC arc.

3)Maximizing solar energy utilization under low irradination.

4) Cost reduction: reduce or cancel the cost of wire, junction box, junction cabinet, inverter room and step-up transformer.

5)Making different PV strings connected in series is suitable for the PV system installed on the barren slope and other complex geographic environment. Different PV array shape, installation area and angle result in difficulties to connect in series.

6)Energy storage battery can improve the quality of the grid current and meanwhile make sure the PV system has a three-phase balanced output.

Ⅵ CONCLUSION

There are still some problems of applying centralized- and string-type PV generation in large-scale photovoltaic power stations. In this paper, focusing on the problem in the centralized and string topologies, a novel PV station structure based on the cascade topology is proposed. By connecting three series branches to a common battery storage, the novel system can be operated in multiple modes. Through detailed theoretical analysis, we can conclude that the proposed topology has the promising advantages including three-phase balanced output, power quality improvement and maximizing the utilization of PV energy in weak irradiation or power restriction.

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