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THE IMPACT OF THE UTILITY-SCALE PHOTOVOLTAIC POWER PLANT ON THE TRANSMISSION GRID IN TERMS OF VOLTAGE AND REACTIVE POWER

Vladimir Budimir & Petar Marić

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Abstract

In the time of high demand for electricity and the transition from the era of dominance of conventional coal-fired power plants to the era of power plants with large installed power whose resources are renewable energy sources, the connection of such power plants directly to the transmission network is becoming increasingly common. The connection of such energy sources to the high voltage grid represents a certain challenge in regulating the power system. Along with the production of useful active power, there is an increase in the network voltage in the connection hub due to the production of reactive power, which must be maintained within strictly prescribed limits. Some of the ways of regulating reactive power and voltage in the transmission network are transformers with transmission ratio regulation, reactive power compensation devices, ballasts, condenser batteries, synchronous generators, and devices based on power electronics. Power electronics-based devices such as inverters with controlling the amount of reactive power in the node are used in photovoltaic power plants.

Keywords: photovoltaic power plant; voltage regulation; power electronics; inverter.

1. Introduction

It is estimated that in the world by 2050 solar photovoltaic (photovoltaic – PV) power plants will produce about 25% of electricity.[1] Most will be connected to the high-voltage transmission grid directly as large power plants.

The voltage in the transmission system is most often regulated by synchronous generators in power plants, which usually receive information about voltage conditions through the transmission system operator.

The case study transmission network is underloaded, which means that the power system must deal with frequent network overvoltage using different methods of voltage regulation and reactive energy, which is a challenge when connecting large power plants to the transmission network.

In the past, various power generation plants were considered exceedingly minor compared to electricity production in conventional power plants, and they were usually referred to as induction generators (wind power plants) or line inverters (photovoltaic power plants) that cannot regulate voltage and reactive power.

However, the increasing rate of penetration of non-traditional renewable energy, especially from wind and sun, has led to the need to produce electricity from renewable sources to significantly contribute to the regulation of voltage and reactive power of the power system. [1]

This paper deals with the example of connecting a solar photovoltaic power plant with an installed capacity of 8 MW to a 110 kV transmission network.

Modern photovoltaic inverters have a significant dynamic ability to regulate reactive energy, which can be further improved with other regulation equipment to meet the requirements for fitting a new power plant into the power system.

2. Case study PV power plant integration to power system

The power plant case study in this paper refers to the actual photovoltaic power plant group PVPP 1-8. The location of the photovoltaic power plants is in Mediterranean climate conditions with an average annual temperature of 16º at 417 m above sea level. Surfaces of building particles amount to approx. twenty thousand square meters. The useful surface of one photovoltaic power plant is 13,000 m2, while the rest of the area will be free. Photovoltaic power plants will be built on dirt terrain with a slope of 6.6º out of 2480 solar modules placed on an aluminium fixed substructure at an angle of 30º.

To receive the electricity produced in the new photovoltaic power plant, a 110/20 kV transmission ratio substation will be built near the 110 kV transmission line as the simplest way of connecting the power plant to the transmission network.

In addition to the photovoltaic panels, eight inverters with an installed AC power of 150 kW will be used in PVPP 1-8. The output power of the inverters will need to be limited to 124,875 kW so that their total output power corresponds to the installed power of the power plant (output of 8 x 999 kW).

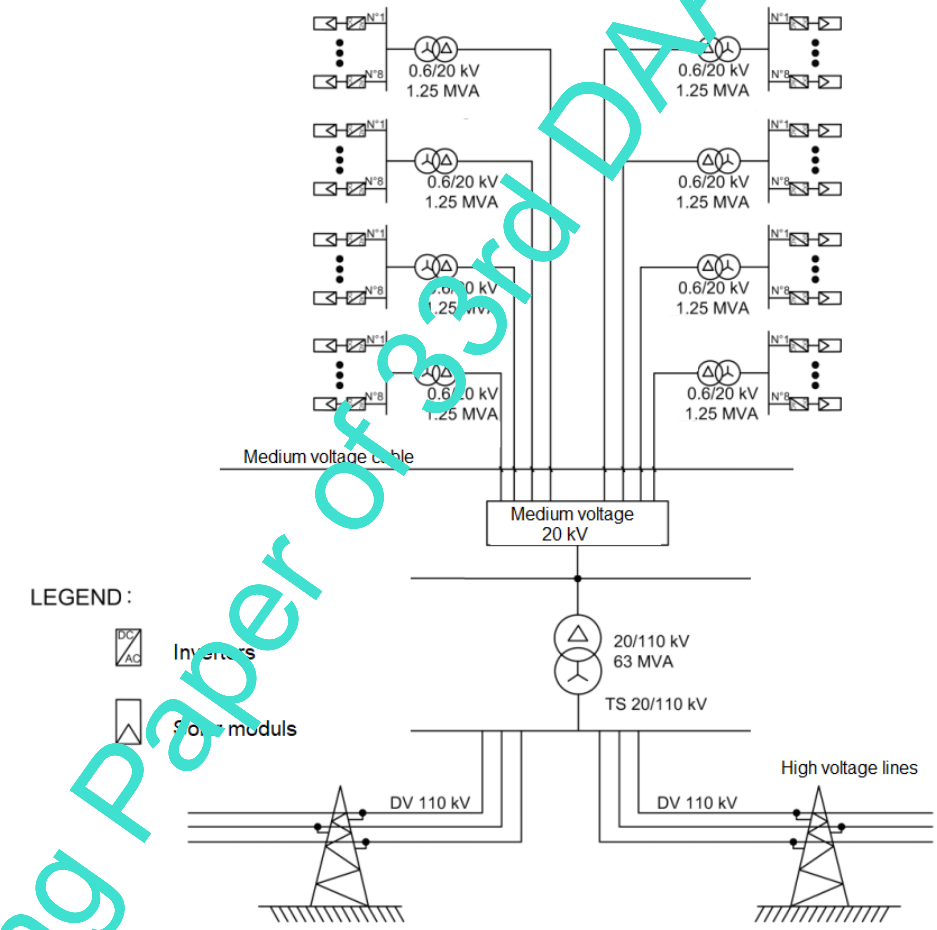

Fig. 1. Block diagram of the internal cable 20 kV grid

2.1. Reactive capability and interconnecting requirements for PV power plants

The difference between inverters and synchronous machines commonly used for reactive power compensation is that they are not power-limited but are limited by internal voltage, temperature, and electric current limitations.

PV inverters were originally designed for installation in the distribution system, where applicable interconnection standards do not allow voltage regulation. Inverters for that application are designed to operate at a unity power factor and are sold with a kilowatt unit designation [kW], as opposed to kilovolt-amperes [kVA].

With the increased use of PV inverters on the transmission grid, the industry is moving towards the ability to provide voltage regulation capabilities through reactive power. Some PV inverters can absorb or inject reactive energy, as needed, provided the current and voltage are not exceeded.

Considering that the cost of the converter is related to the rated current, providing reactive power at full capacity means that the converter power must be higher for the same plant power.

Inverters could produce or absorb reactive power in power states lower than P1 (P2).

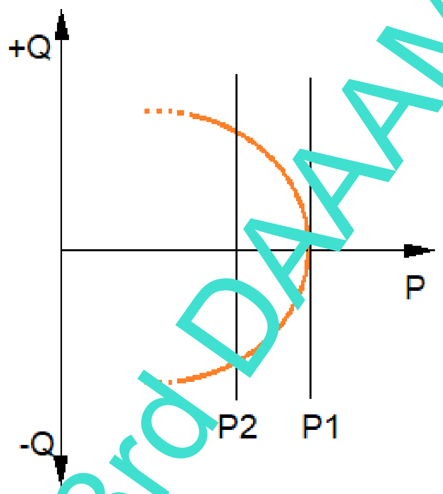

Fig. 2. Inverter reactive power capability (orange) based on electric current limitation

PV inverters are usually disconnected from the grid at night, in which case the inverter-based reactive power voltage regulation capability is not available.

The characteristics of the power system cannot be significantly influenced if connects power plants as in this case. To produce reactive power, it is possible to act by controlling the inverter and the transmission ratio of the connected one’s transformer. For this reason, in calculations and simulations, a constant value of the short-circuit voltage is most often used and the influence of the change in the transfer ratio of the connection transformers on the different operating modes of the inverter is analysed. Figure 3 defines the conditions regarding power and voltage at the point of connection of the power plant to the transmission network.

In this way, it is not necessary to separately analyse individual states of the system in analysed regimes, but only the configuration of the photovoltaic power plant.

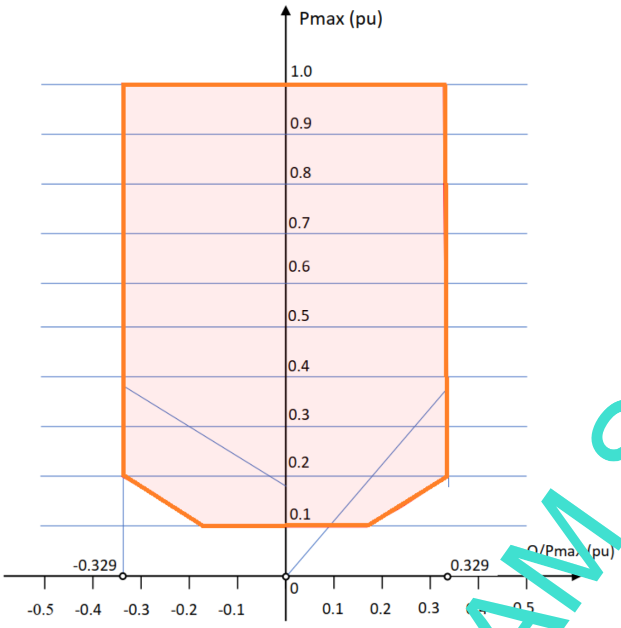

Fig. 3. Inverter reactive power capability (orange) based on electric current limitation

2.2. Inverters

Solar inverters convert the direct voltage of the solar modules into the alternating voltage of the regulated amount and frequency, synchronized with the voltage of the distribution network.

The characteristics of the solar grid inverter *SMA Sunny Highpower* 150-20 (150 kW) are given in Figure 3.

The minimum requirement for parallel operation is that the inverter protection works and isolates the PV system from the grid if there is a deviation from the voltage (overvoltage or undervoltage) or frequency (over and under), and deviations from factory settings (programmed for each inverter). SMA Sunny Highpower 150-20 inverters meet the requirements for protective functions and inverter adjustment limits according to EU standards and network rules of the distribution system operator.

The inverters are a renowned product, and they combine all the circuits necessary for safe and reliable operation on the low-voltage grid.

Eight inverters types like SMA Sunny Highpower 150-20 (150 kVA) will be used.

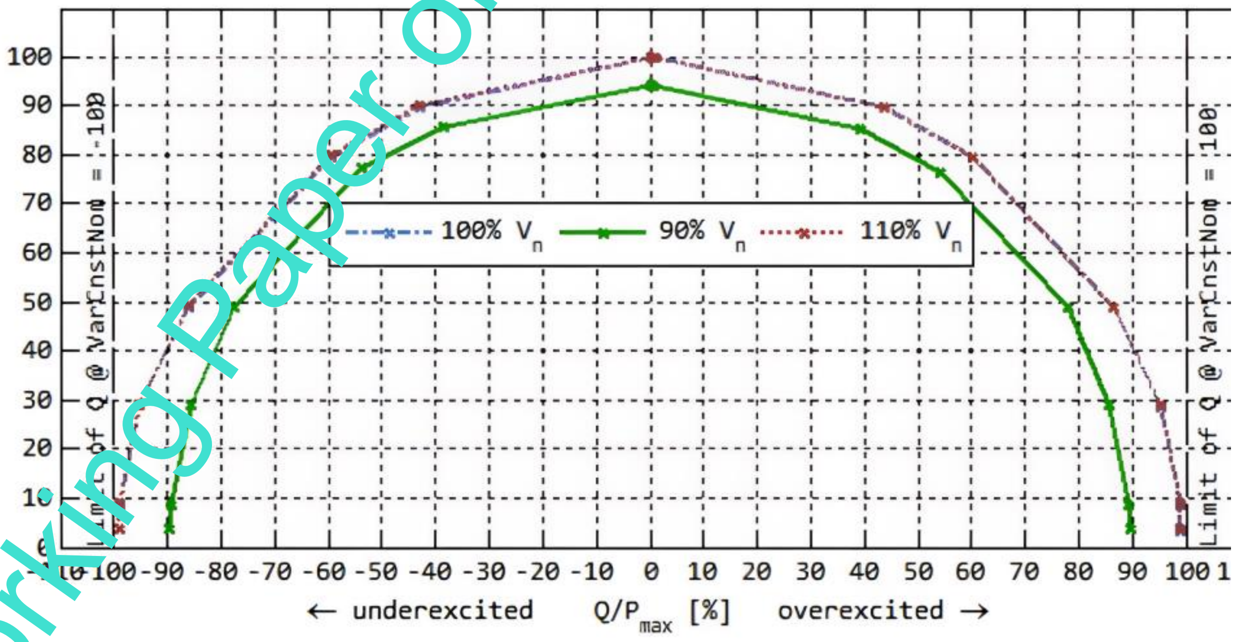

Fig. 3. Operating map SHP 150k-20 SMA (PQ characteristics)

The operating map shows the complex relationship between active power and voltage, and the reactive capability of the inverter.
Given that the mentioned characteristics are modelled and slightly approximated to the database provided by the inverter manufacturer, the following tables are presented delivered measured values based on which the characteristics are given and modelled.

P_{DC}/P_{max}	U [V]	P/Sn [%]	Q_u/S_n [%]	P/S_n [%]	Qo/S_n [%]	VarCnstNom
5%	599.68	3.57	-98.96	3.54	98.77	-99.9/99.9
10%	599.61	8.63	-98.90	8.6	98.78	-99.5/99.5
30%	599.59	28.84	-95.17	28.66	95.29	-95.4/95.4
50%	599.59	49.06	-86.06	48.81	86.63	-86.6/86.6
80%	599.56	79.64	-59.58	79.27	60.39	-60.0/60.0
90%	599.57	89.73	-42.74	89.58	43.88	-43.6/43.6
100%	599.57	99.83	0.14	99.75	0.87	0.0/0.0
5%	539.73	3.55	-89.84	3.59	89.65	-89.9/89.9
10%	539.67	8.63	-89.39	8.64	89.31	-89.5/89.5
30%	539.64	28.83	-85.57	28.82	85.71	-85.8/85.8
50%	539.63	48.98	-77.38	48.91	77.93	-77.9/77.9
80%	539.61	77.17	-53.60	76.57	54.36	-54.0/54.0
90%	539.63	85.67	-38.39	85.24	39.46	-39.2/39.2
100%	539.65	93.98	0.13	93.93	0.71	0.0/0.0
5%	659.70	3.82	-98.99	3.85	98.73	-99.9/99.9
10%	659.65	8.89	-98.92	8.89	98.74	-99.5/99.5
30%	659.63	29.11	-95.18	28.92	95.26	-95.4/95.4
50%	659.64	49.32	-86.05	49.06	86.61	-86.6/86.6
80%	659.60	79.89	-59.61	79.38	60.40	-60.0/60.0
90%	659.61	89.98	-42.80	89.64	43.88	-43.6/43.6
100%	659.62	99.87	0.16	99.80	0.81	0.0/0.0

Table 1. Reactive production limits of the inverter for different values of voltage

3. Case study model

The first step in modelling the connection of the power plant to the grid is the creation of a credible model of the local transmission network. The Neplan software tool was used for the model. [4]

By entering the length of transmission lines, associated impedances, existing production, and a load of the local network, a model of the 110 kV ring to which the modelled 8 MW power plant will be connected was made.

A model consists of eight substations connected by 110 kV transmission lines. A feeding element has been added, as well as loads that simulate loads in real-time and production from a nearby hydroelectric power plant (120 MW).

The case study power plant model used in this paper is being connected to similar grid model that the authors have already worked on and concerns a local 110 kV ring network. [3]

The model calculation requires data on the observed transmission lines such as conductor type, transmission line length, line constants, voltage level etc. [3][5][6].

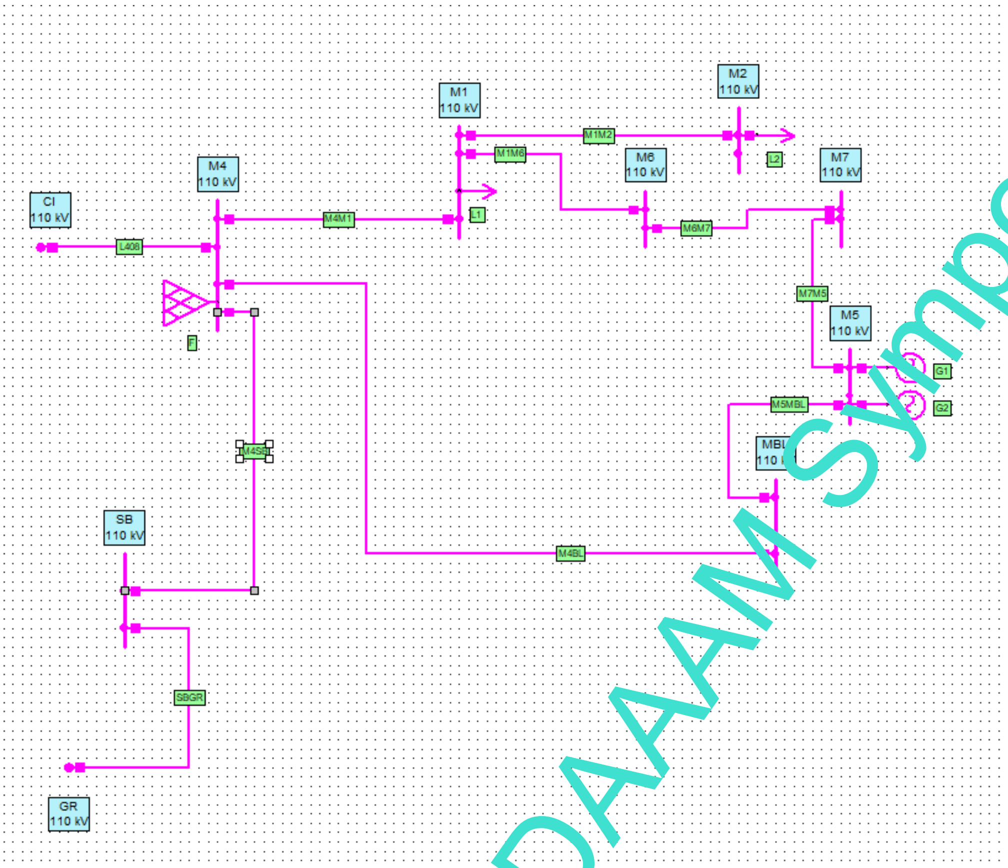

Fig. 4. 110 kV grid model

After all the parameters have been adjusted and all the alerts requested by the program have been eliminated, the calculation was performed. What was important to read from this iteration were the voltage conditions in the nodes. This data is needed so that after the connection of the power plant with the possibility of reactive power regulation via inverter as a utility, the new voltage conditions could be compared with those before the connection of the photovoltaic power plant and certain conclusions could be drawn about this type of regulation.

Busbar/Node	Voltage Level [kV]	The voltage before connecting PVPP 1-8 [kV]
CI	110	112.45
GR	110	112.40
M1	110	113.50
M2	110	113.06
M4	110	113.28
M5	110	113.14
M6	110	113.13
M7	110	113.05
MBL	110	113.22
SB	110	112.57

Table 2. Voltages per node before connecting PVPP 1-8

After extracting the necessary data of the grid model in the maximum mode of operation, the network model was further created in such a way that a new 110 kV substation was integrated into the existing 110 kV transmission line, through which the produced electricity from the photovoltaic power plant PVPP 1-8 will be injected directly into the 110 kV grid.

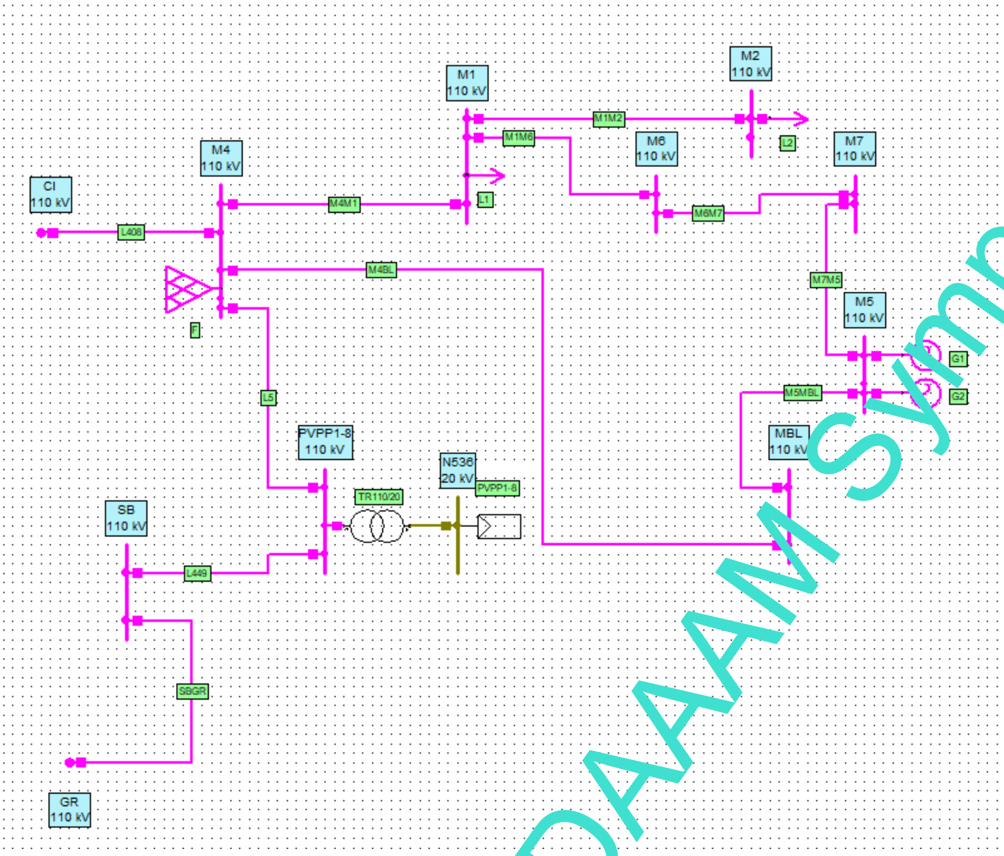

Fig. 5. PVPP 1-8 integrated into local 110 kV power grid

Busbar/Node	Voltage Level [kV]	Voltage after connecting PVPP 1-8 [kV]
CI	110	112.43
GR	110	112.47
M1	110	113.48
M2	110	113.04
M4	110	113.26
M5	110	113.11
M6	110	113.12
M7	110	113.03
MBL	110	113.19
SB	110	112.55
PVPP 1-8	110	113.30

Table 3. Voltages per node after connecting PVPP 1-8

The voltages in all nodes after connecting PVPP 1-8 to the transmission 110 kV level are above the nominal value but are within the permitted deviations. After the connection of the case study PV power plant into the power system, there is an insignificant reduction in voltage at most substations (Table 4., except in GR) in the local EES compared to the state before connection. The voltage on the 110 kV buses of the new substation PVPP 1-8 is 113.3 kV. The connection of the case study PVPP into the local power system's normal regime has a negligible impact on the transmission network because most of the power is placed in node M4, and because of that there is an insignificant change in the voltage conditions.

Busbar/Node	The voltage before connecting PVPP 1-8 V_B [kV]	Voltage after connecting PVPP 1-8 V_A [kV]	$\Delta V_A V_B$
CI	112.45	112.43	-0.02
GR	112.40	112.47	0.07
M1	113.50	113.48	-0.02
M2	113.06	113.04	-0.02
M4	113.28	113.26	-0.02
M5	113.14	113.11	-0.03
M6	113.13	113.12	-0.01
M7	113.05	113.03	-0.02
MBL	113.22	113.19	-0.03
SB	112.57	112.55	-0.02

Table 4. Voltage difference before and after the connection of PVPP 1-8

4. Conclusion

By analysing the model created as a substitute local 110 kV ringnetwork in the Neplan tool according to the data used and the structure of the local transmission 110 kV system in the vicinity of the future photovoltaic power plants, it can be concluded that the transmission network of the local electricity power system provides reliable and adequate power supply to the connected consumers. The analysis of the junction voltage shows that the voltage changes in the nearby 110 kV junctions are minor.

Voltages in most 110 kV nodes in the local power system are slightly reduced but remain within the prescribed limits.

Based on the performed analysis of the fulfilment of (n-1) safety criteria, it can be concluded that the connection of PVPP 1-8 to the transmission network does not violate the safety requirements according to this criterion.

Of course, the analysis of this paper refers to voltage regulation via built-in inverters and does not consider other types of voltage and reactive power regulation.

5. Acknowledgments

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