Reactive power comparison between central and string inverter

Revision 03

04 March 2026

TABLE OF CONTENTS

EXECUTIVE SUMMARY **4**

1. INTRODUCTION **5**

2. KEY TECHNICAL OBSERVATIONS **6**

2.1 Central inverter 6

2.2 String inverter 7

3. P-Q CAPABILITY **9**

3.1 Grid Code Requirement 9

3.2 Central inverter 9

3.3 String configuration 10

4. RESULTS **12**

5. CONCLUSION **14**

APPENDICES **15**

APPENDIX A – MODELLING INPUT DATA **16**

A.1 Central configuration 16

A.2 String configuration 18

APPENDIX B – LAYOUT OF THE PV PLANTS **20**

FIGURES

Figure 1 PV panels and inverter 5
Figure 2 Connection Diagram of the Central inverter 7
Figure 3 Connection Diagram of the String inverter 8
Figure 4 Power-DC Input Voltage Curve 8
Figure 5: Observed Grid Code 9
Figure 6: PQ curve at 40 degC, with Vdc within MPPT range, central inverter 10
Figure 7 PQ curve at 20 degC, with Vdc outside MPPT range(780V), central inverter 10
Figure 8: PQ curve at 40degC, with Vdc within MPPT range, string inverter 11
Figure 9: PQ curve at 20degC, with Vdc outside MPPT range for rated power (500V), string inverter 11

TABLES

Table 1 - Main technical parameters of central inverter 6
Table 2 - Main technical specifications of string inverter 7
Table 3 - Central inverter configuration under reactive power absorption conditions 12
Table 4 - Central inverter configuration under reactive power injection conditions 13
Table 5 - String inverter configuration under reactive power absorption conditions 13
Table 6 - String inverter configuration under reactive power injection conditions 13
Table 7 - 400/33/33 kV 620MVA main transformer parameters 16
Table 8 - 33kV/0.6kV/0.6kV inverter transformer 17
Table 9 - Cable Parameters 17
Table 10 - 33kV/0.8kV/0.8kV inverter transformer 18
Table 11 - Cable Parameters 19

EXECUTIVE SUMMARY

In this study, a comparison between photovoltaic (PV) power plants based on central inverters and those using string inverters is presented. The analysis is specifically focused on reactive power provision and the assessment of compliance with the PQ capability curve defined in the applicable Grid Code. Attention is given to the impact of reduced DC input voltage on inverter performance, especially during periods of low solar irradiance.

The results demonstrate that string inverters, due to their integrated DC/DC converter stage (MPPT), can regulate and adapt to DC voltage fluctuations more effectively than central inverters. This capability allows string inverters to maintain operation and provide reactive power support even when the DC voltage drops below nominal values.

In conclusion, under low irradiance conditions, such as early morning hours, a PV power plant based on central inverters may fail to meet Grid Code requirements due to insufficient reactive power capability caused by low DC voltage levels. In contrast, a PV power plant based on string inverters does not face this limitation, as its design enables continued reactive power provision despite reduced DC input voltage.

Therefore, string inverter configurations offer improved operational flexibility and enhanced compliance with grid requirements under varying environmental conditions.

1. INTRODUCTION

As modern grid codes increasingly require photovoltaic (PV) power plants to contribute to voltage control throughout the entire day, it becomes essential to accurately assess how different inverter technologies perform and what advantages or limitations they may introduce. This project compares PV power plants equipped with **central inverters** to those using **string inverters**, with particular emphasis on their ability to deliver reactive power and support grid voltage regulation in compliance with national Grid Code requirements.

The analysis focuses on how variations in DC voltage at the inverter input influence reactive power capability of the inverters.

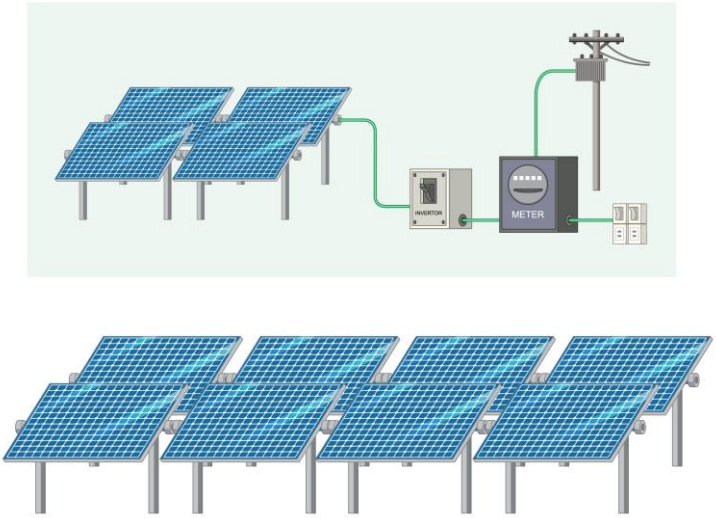


Figure 1 PV panels and inverter[1]

A key aspect of this study is to demonstrate that during periods of low solar irradiance—such as early morning—the reduced DC voltage from the PV panels can constrain the reactive power output of central inverters. By contrast, string inverters are generally able to continue supplying reactive power under the same conditions, primarily due to differences in their electrical configuration and operational characteristics.

To evaluate these effects, the PowerFactory DIgSILENT software was used to model two large-scale PV power plant configurations: one employing string inverters and the other central inverters. Both plants are assumed to be located in the Abu Dhabi region of the United Arab Emirates, with the installed capacity of 1.37 GW for the string inverter configuration, and 1.39 GW installed capacity for the central inverter configuration.

The technical parameters of the electrical equipment used to ensure the safe connection of the inverters to the grid within the Power Factory (PF) model, will be presented in Appendix A of this document. Appendix B will provide an overview of the PV plant layout for both configurations: the central-inverter setup and the string-inverter setup.

Developed PF models shall serve as the basis for analyzing reactive power behavior under varying DC voltage conditions.

[1] *Designed by brgfx / Freepik.*

2. KEY TECHNICAL OBSERVATIONS

2.1 Central inverter

Technical parameters of the central inverter, essential for this analysis, are presented in Table 1 below:

Table 1 - Main technical parameters of central inverter

1100kVA central inverter	
Input (DC)	
Max. PV input voltage	1500 V
Min. PV input voltage / Startup input voltage	895 V / 905 V
Normal voltage range	895 – 1500 V
Output (AC)	
AC output power	1100 kVA
Max. AC output current	1160 A
Nominal AC voltage	630 V
AC voltage range	536 – 693 V
Nominal grid frequency / Grid frequency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz
Harmonic (THD)	< 3 % (at nominal power)
Power factor at nominal power / Adjustable power factor	> 0.99 / 0.8 leading – 0.8 lagging
Feed-in phases / AC connection	3/3
Max. efficiency / European efficiency	99.0 % / 98.7 %

What is immediately visible is that the normal voltage range is constrained to 895V-1500 V_{DC}. The diagram shown in Figure 2 below illustrates the connection scheme of the central inverter.

The technical parameters abovementioned indicate that the inverter is not operational for voltages below 895 V_{DC} or above 1500 V_{DC}.

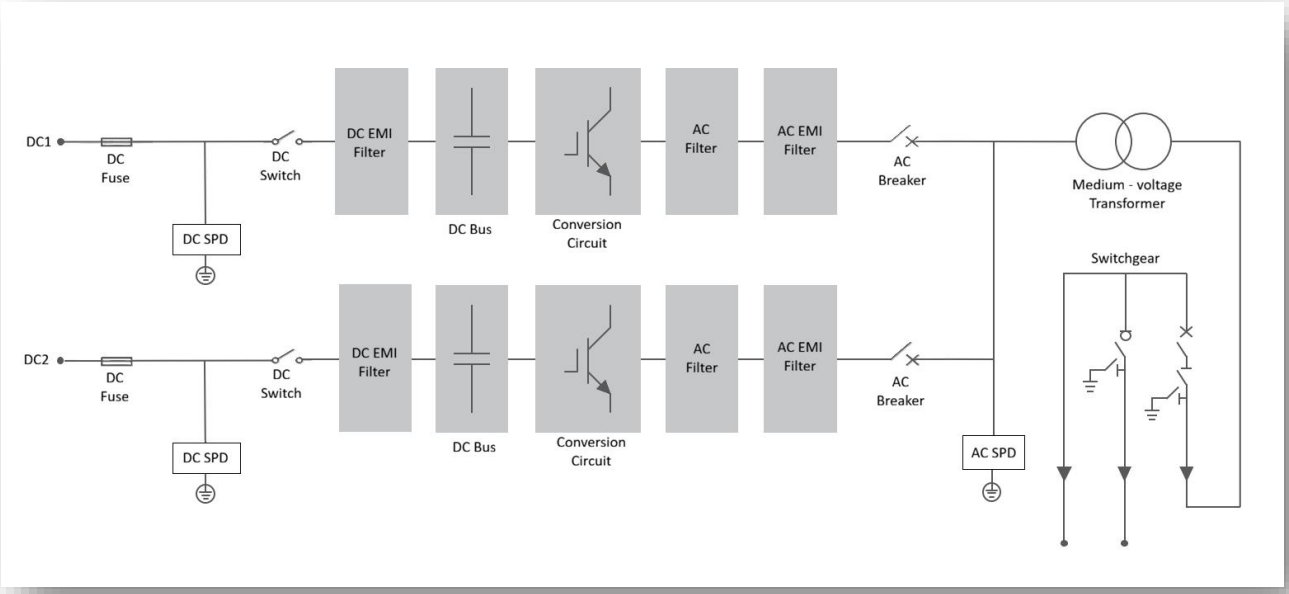


Figure 2 Connection Diagram of the Central inverter

2.2 String inverter

Technical parameters of the string inverter, essential for this analysis, are presented in Table 2 below:

Table 2 - Main technical specifications of string inverter

330kVA central inverter	
Input (DC)	
Max. PV input voltage	1500 V
Min. PV input voltage / Start-up input voltage	500 V / 550 V
Nominal PV input voltage	1080 V
MPP voltage range	500 V – 1500 V
MPP voltage range for nominal power	880 V – 1320 V
No. of independent MPP inputs	6
Output (AC)	
AC output power	330kVA
Nominal AC voltage	3W + PE, 800 V
Nominal grid f requency / Grid f requency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz
Power factor at nominal power / Adjustable power factor	> 0.99 / 0.8 leading – 0.8 lagging
Feed-in phases / AC connection	3/3
Max. efficiency / European efficiency	99.0 % / 98.8 %

A key distinction of string inverter technology is that its technical specifications define two separate DC voltage ranges:

- one for operating at nominal power and
- another for delivering power below nominal levels.

Nominal AC output can be achieved when the MPPT input voltage is maintained within the 880–1320 V DC range. The MPPT device, shown in the diagram, operates as a DC/DC converter that adjusts the PV array voltage to track the maximum power point, ensuring operation within its specified MPPT voltage range. This ensures that the DC bus voltage remains stable, allowing the DC/AC conversion stage to operate efficiently and deliver apparent power close to the inverter's rated capacity. The connection scheme of the string inverter is illustrated in Figure 3 below.

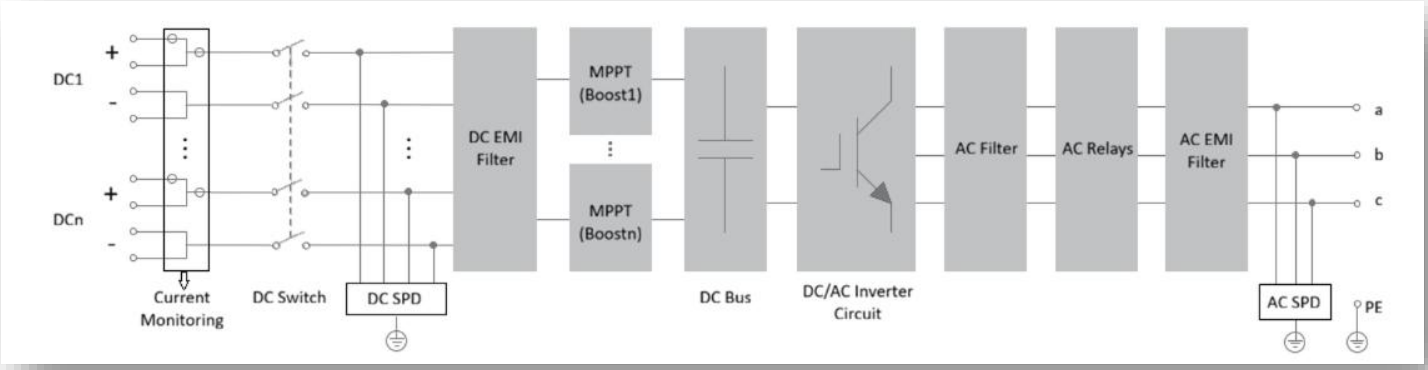


Figure 3 Connection Diagram of the String inverter

However, the technical parameters abovementioned indicate that the inverter is also operational for voltages outside this range, but with their active power output being reduced.

The relationship between the inverter's output power and the input DC voltage is illustrated in Figure 4 below.

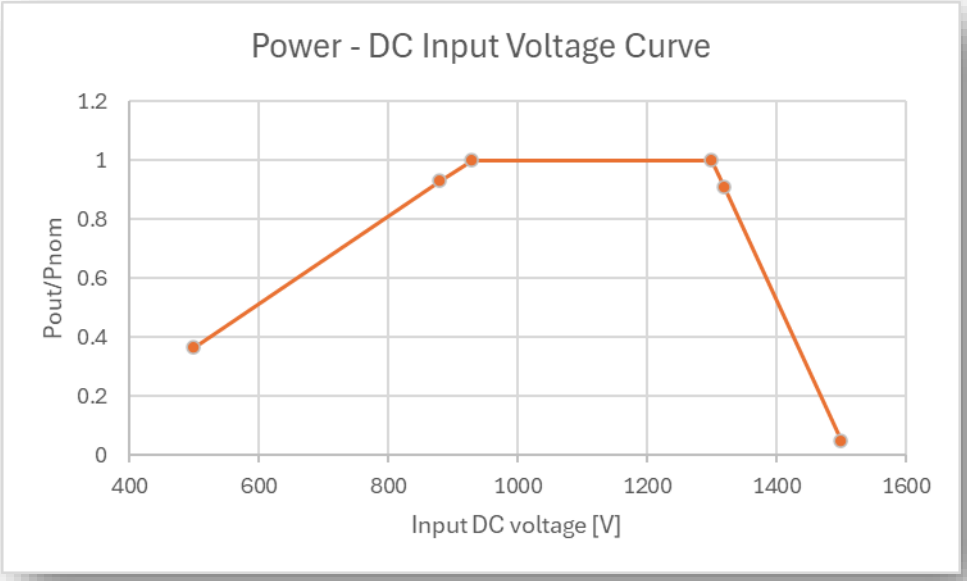


Figure 4 Power-DC Input Voltage Curve

3. P-Q CAPABILITY

3.1 Grid Code Requirement

According to observed Grid Code Requirements for Active and Reactive Power Capability, the Power Park Module should provide reactive power to the maximum possible extent, but not less than ±33% of the rated power. This corresponds to power factor of 0.95 leading/lagging and shall be applicable for any level of active power, including zero active power. Also, this shall apply to any voltage at the connection point within the limits of 0.9-1.1pu.

P-Q capability diagram requirements for power park modules are given in Figure 5 below:

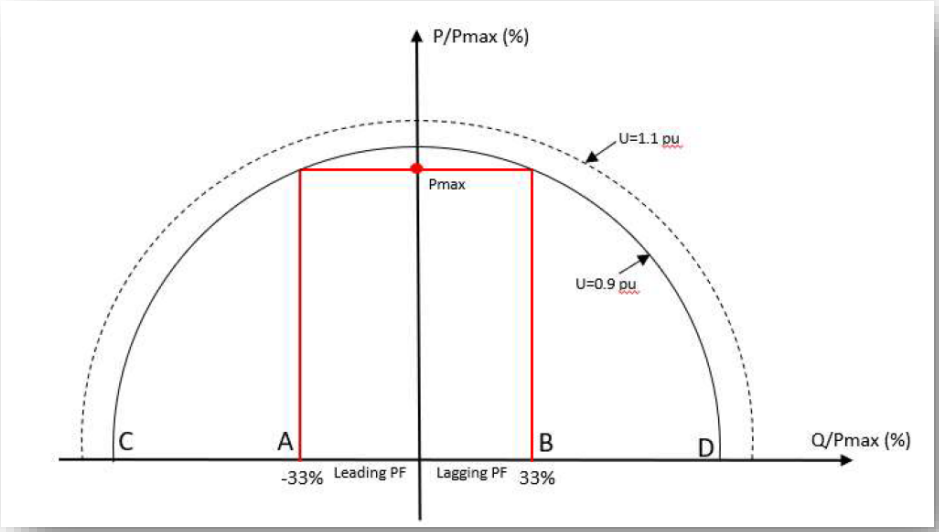


Figure 5: Observed Grid Code

To comply with the Grid Code requirements, observed PV plant must be capable of supplying ±435.9 Mvar for central inverter configuration and ±430.4 Mvar for string inverter configuration, so that power factor of 0.95 leading/lagging could be achieved.

3.2 Central inverter

The active and reactive power capabilities of the central inverter which were evaluated as part of this analysis are illustrated through P-Q curves:

- Figure 6: PQ curve at 40 degC, central: This figure illustrates the operation of the central inverter when the input DC voltage is within the range 895-1500V. The graph indicates three different ranges, depending on the voltage at the 400kV Point of Connection (0.9Vnom, 1Vnom, 1.1Vnom).

- Figure 7 PQ curve at 20 degC, central: This figure illustrates the operation of the central inverter when the input DC voltage falls below 895 V (780V). Although the datasheet referenced in Section 2.1 states that the inverter cannot operate in this voltage range, the graph is based on discussions and hands-on experience of an inverter manufacturer. According to the manufacturer, the inverter can still inject reduced active power (around 30% of nominal value) and the reactive power at low DC voltages, but only up to 75% of the expected value, for the reactive power. This limitation occurs because the inverter configuration cannot deliver full reactive power output when the DC input voltage is below a certain value for which it was projected. It can be considered, for the

purpose of this analysis that this curve is adequate for three different ranges of the voltage at the 400kV Point of Connection (0.9Vnom, 1Vnom, 1.1Vnom).

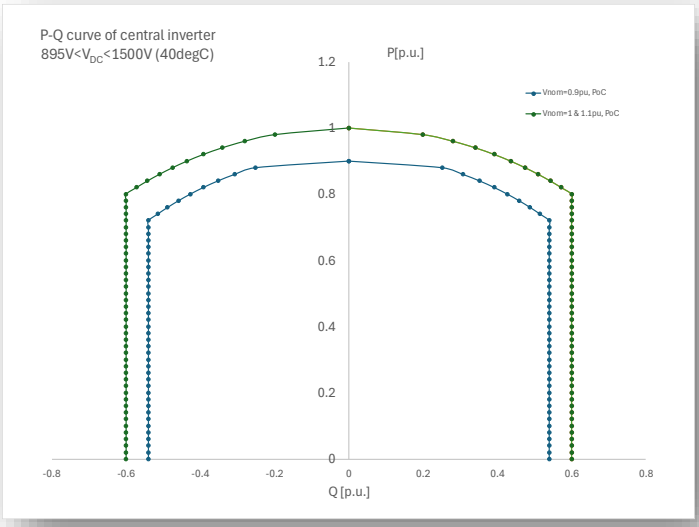


Figure 6: PQ curve at 40 degC, with Vdc within MPPT range, central inverter

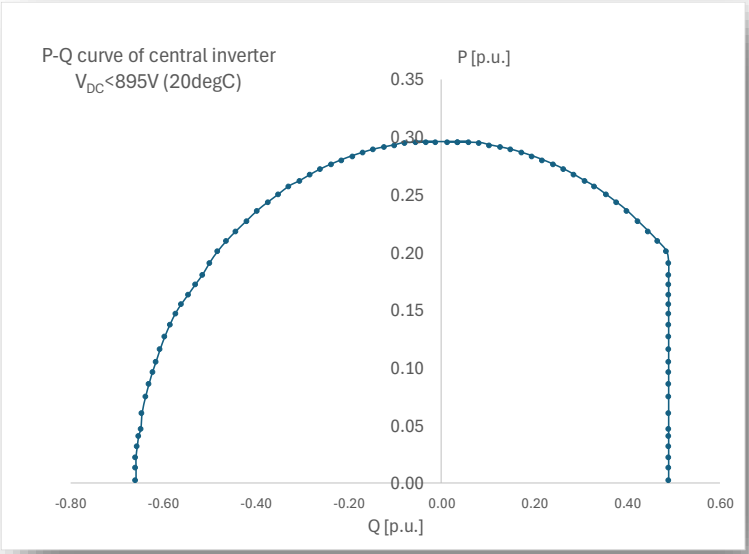


Figure 7 PQ curve at 20 degC, with Vdc outside MPPT range(780V), central inverter

3.3 String configuration

The active and reactive power capabilities of the string inverter which were evaluated as part of this analysis are illustrated through P-Q curves:

- Figure 8: PQ curve at 40degC, with Vdc within MPPT range, string inverter: This figure illustrates the operation of the string inverter when the DC input is within the range 880-1320V. The graph

includes three different ranges, depending on the voltage at the 400kV Point of Connection (0.9Vnom, 1Vnom, 1.1Vnom).

- Figure 9: PQ curve at 20degC, with Vdc outside MPPT range for rated power (500V), string inverter: This figure illustrates the operation of the string inverter when the input DC voltage falls below 880 V (500V). According to the manufacturer, the inverter can still inject reduced active power (around 33% of nominal value) and deliver the full reactive power range.

  The string inverter is capable of supplying both active and reactive power to the grid, with reactive power support available in both lagging and leading operating modes.

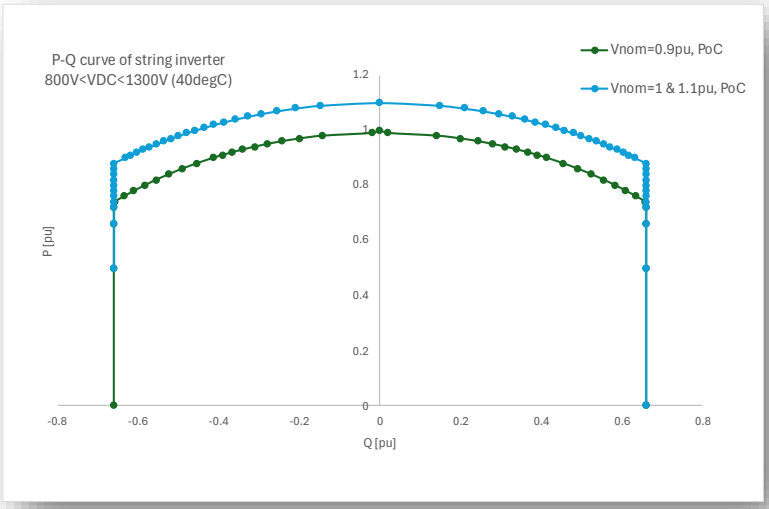


Figure 8: PQ curve at 40degC, with Vdc within MPPT range, string inverter

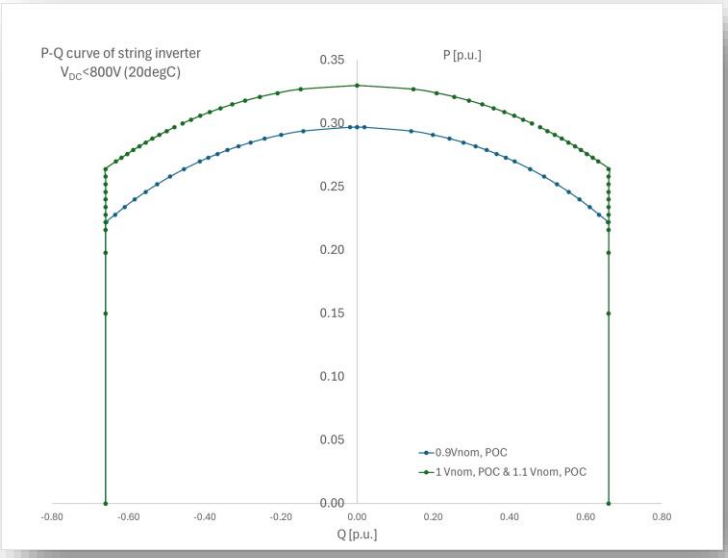


Figure 9: PQ curve at 20degC, with Vdc outside MPPT range for rated power (500V), string inverter

4. RESULTS

Within this study, simulations were performed in DIgSILENT PowerFactory for the previously described system configurations. The objective was to verify compliance with the national Grid Code (illustrated in Section 3.1). Accordingly, the boundary operating points defined by the grid code were assessed at the point of connection (PoC) for voltage levels of 0.9 p.u., 1.0 p.u., and 1.1 p.u.

The simulations were carried out for midday and morning operating conditions of a typical summer day in the region. The corresponding results are presented in the tables below.

Operating modes in which the power plant absorbs reactive power from the grid as well as those in which it injects reactive power into the grid were investigated.

In accordance with the simulated daily operating conditions, appropriate P–Q capability curves were implemented:

- Full active power output, and the curves corresponding to an ambient temperature of 40°C – conditions for 01:00 PM scenario.
- Active power output of 30-33%, depending on the time of the day and respective irradiance, and the curves corresponding to an ambient temperature of 20°C – conditions for 09:00 AM scenario.

During the simulations, the voltage operating limits of the 400 kV and 33 kV busbars were also considered, as outlined below:

- Voltage variations at 400kV: ±5%,
- Voltage variations at 33kV: ±10% (controlled by 400/33/33kV transformer taps),

The results are presented in the following tables.

Table 3 - Central inverter configuration under reactive power absorption conditions

	Time	Case No.	Voltage at POC [pu]	Active Power at POC [MW]	Reactive Power at POC [Mvar]	Grid Code requirement [Mvar]	Fulfilling Criteria?
Central	1PM	1	0.9	1000	-435.9	-435.9	Yes
		2	1		-435.9	-435.9	Yes
		3	1.1		-435.9	-435.9	Yes
	9AM	4	0.9	391	-348.9	-435.9	No
		5	1		-338.7	-435.9	No
		6	1.1		-337.6	-435.9	No

Table 4 - Central inverter configuration under reactive power injection conditions

	Time	Case No.	Voltage at POC [pu]	Active Power at POC [MW]	Reactive Power at POC [Mvar]	Grid Code requirement [Mvar]	Fulfilling Criteria?
Central	1PM	1	0.9	1000	435.9	435.9	Yes
		2	1		435.9	435.9	Yes
		3	1.1		435.9	435.9	Yes
	9AM	4	0.9	391	187.9	435.9	No
		5	1		189.8	435.9	No
		6	1.1		193.5	435.9	No

The results show that the configuration using a central inverter does not comply with Grid Code requirements during the 09:00 AM scenario, where the PV plant absorbs or injects reactive power. However, it does satisfy the Grid Code criteria under the observed midday operating condition (1:00 PM).

Table 5 - String inverter configuration under reactive power absorption conditions

	Time	Case No.	Voltage at POC [pu]	Active Power at POC [MW]	Reactive Power at POC [Mvar]	Grid Code requirement [Mvar]	Fulfilling Criteria?
String	1PM	1	0.9	1000	-430.4	-430.4	Yes
		2	1		-430.4	-430.4	Yes
		3	1.1		-430.4	-430.4	Yes
	9AM	4	0.9	385	-430.4	-430.4	Yes
		5	1		-430.4	-430.4	Yes
		6	1.1		-430.4	-430.4	Yes

Table 6 - String inverter configuration under reactive power injection conditions

	Time	Case No.	Voltage at POC [pu]	Active Power at POC [MW]	Reactive Power at POC [Mvar]	Grid Code requirement [Mvar]	Fulfilling Criteria?
String	1PM	1	0.9	1000	430.4	430.4	Yes
		2	1		430.4	430.4	Yes
		3	1.1		430.4	430.4	Yes
	9AM	4	0.9	385	430.4	430.4	Yes
		5	1		430.4	430.4	Yes
		6	1.1		430.4	430.4	Yes

The results show that the configuration using a string inverter does comply with Grid Code requirements during both 09:00 AM and 01:00PM scenarios, where the PV plant absorbs or injects reactive power.

In the reactive power absorption conditions, for 0.9p.u. at the connection point, changing tap positions had to be employed, to keep the voltages at 33kV within the limits (taps set to tap position: -10).

In the reactive power injection conditions, for 1.1p.u. at the connection point, changing tap positions had to be employed, to keep the voltages at 33kV within the limits (taps set to tap position: 10).

5. CONCLUSION

This study assessed the reactive power capability of a PV power plant using two system configurations—central and string inverters—through detailed DIgSILENT PowerFactory simulations, with the goal of evaluating compliance with the national Grid Code.

The analysis was carried out at the point of connection for voltage levels of 0.9 p.u., 1.0 p.u., and 1.1 p.u., considering both reactive power absorption and injection during representative morning and midday summer operating conditions. P–Q characteristics were obtained from manufacturer datasheets and technical discussions with industry representatives.

The main findings are:

- **Central inverter configuration**:
  The Grid Code requirements are not met during the morning scenarios. This limitation comes from the inverter's inability to raise the low DC voltage due to its internal design. It should be emphasized that the central inverter is not intended to operate under DC voltage conditions below those specified in its datasheet.

- **String inverter configuration**:
  The Grid Code requirements are satisfied. The MPPT device within the inverter (operating as a buck–boost converter) successfully increases the low DC voltage, allowing inverter operation even when the DC link voltage falls below its nominal range. String inverters are designed to operate under reduced DC voltages, though with correspondingly reduced active power output.

Overall, the results indicate that string inverters represent a more optimal solution for large PV plants. Their distributed MPPT architecture enables independent optimization of PV strings. Additionally, string inverters reduce installation complexity and DC cable losses due to shorter cable runs and lower DC currents.

APPENDICES

Appendix A - Simulation Input Data

Appendix B – Layout of the PV plants

- Central inverter configuration
- String inverter configuration

APPENDIX A – MODELLING INPUT DATA

The input data and technical parameters for both technologies are taken from publicly available industry documents, books, and standards. However, specific manufacturer names are intentionally omitted, as the purpose of this work is not commercial promotion but to illustrate fundamental technical principles.

The following sections describe the modeling approach used for the power plant, covering both inverter configurations. The models comprise the following components:

- HV/MV/MV transformers,
- MV/LV/LV transformers,
- 400 kV cables,
- 33 kV cables,
- 0,8 kV cables,
- 0,6 kV cables,
- PV inverters.

In addition, the input data for each individual system component are provided in the subsequent sections.

A.1 Central configuration

PV plant is connected to the grid through three main 400/33/33 kV transformers, whose specifications are summarized in Table 7. These network transformers are connected to the point of connection through 400 kV cables with a length of 0.345 km and the ampacity of 917 A.

Table 7 - 400/33/33 kV 620MVA main transformer parameters

Parameter	Unit	Value
Type		Oil immersed
Rated power	MVA	620
Number of phases		3
Number of windings		3
Primary Voltage	kV	400
Secondary Voltage	kV	33/33
Type of tap changer		On-load
Vector Group		YNd11d11
Frequency	Hz	50
Through impedance Uk (HV/(LV1+LV2)) [620MVA basis]	%	33
Half-through impedance Uk (HV/LV1), Uk (HV/LV2) [310 MVA basis]	%	29
Half-through impedance Uk (LV1/LV2) [310 MVA basis]	%	51
No-load losses	kW	170
Load losses at rated power HV to (LV1+LV2)	kW	1600

In total, the network includes central inverters rated 1100kVA and 158 inverter transformers (details disclosed in Table 8). Eight central inverters are connected to each of the inverter transformers, four

inverters on the secondary side of the transformer, and the remaining four on the tertiary side. This configuration has a total of 1264 inverters. The specifications of the inverters are provided in Table 1.

Table 8 - 33kV/0.6kV/0.6kV inverter transformer

Parameter	Unit	Value
Rated power	MVA	8,8
Number of phases		3
Number of windings		3
Primary Voltage	kV	33
Secondary Voltage	kV	0,6/0,6
Type of tap changer		On-load
Vector Group		Dy11y11
Frequency	Hz	50
Half-through impedance Uk (HV/LV1), Uk (HV/LV2)	%	8,28
Half-through impedance Uk (LV1/LV2)	%	14,07
No-load losses	kW	170
Load losses at rated power HV to LV	kW	7

The main 400/33/33 kV, 620 MVA transformers and the 400 kV PoC busbar are connected using 400 kV, 800 mm² XPLE single-core cables. The 33 kV side of the main transformers is linked to the 33 kV busbar via five 33 kV, 630 mm² XPLE single-core cables.

PV blocks are connected to the 33 kV switchgear through 33 kV, 500 mm² underground aluminium XPLE cables, while internal connections between PV blocks are implemented using 240 mm² underground aluminium XPLE cables. For the connection of PV inverters to the inverter transformers, 0.6 kV underground aluminium XPLE cables with a cross-section of 300 mm² are used.

The parameters of all cables mentioned above are summarized in the Table 9 below.

Table 9 - Cable Parameters

Cross section [mm2]	Voltage	AC resistance [Ohm/km]	Reactance [Ohm/km]	Capacitance [uF/km]	B [s/km]	Current rating [kA]	Rzero [Ohm/km]	Xzero [Ohm/km]
1x800C	400kV	0.0309	0.2540	0.1500	4.71E-05	0.9790	0.0943	0.0969
1x630C	33kV	0.0398	0.1106	0.3420	1.07E-04	0.728	0.1708	0.0583
1x500Al	33kV	0.0794	0.1137	0.3100	9.74E-05	0.5230	0.1709	0.0578
3x240Al	33kV	0.1610	0.1109	0.2440	7.67E-05	0.3380	0.9701	0.0498
3x300Al	0.6kV	0.1310	0.0654	0.6160	1.935E-04	0.2540	0.7893	0.0282

Appendix A contains overview of the entire plant layout, as represented in the Power Factory model.

A.2 String configuration

PV plant is connected to the grid through three main 400/33/33 kV transformers, similar to the ones described in Table 7. These network transformers are again connected to the point of connection through 400 kV cables with a length of 0.345 km and the ampacity of 917 A.

In this model, a total of 26 string inverters, each rated 330kVA, are connected to the 0.8 kV side of each 33/0.8/0.8 kV inverter transformer, with 13 inverters connected to the secondary winding and 13 to the tertiary winding. Total number of inverters in this configuration is 4,160. The model includes a total of 160 inverter transformers of this type, and their technical data is provided in Table 10.

Table 10 - 33kV/0.8kV/0.8kV inverter transformer

Parameter	Unit	Value
Rated power	MVA	9,1
Number of phases		3
Number of windings		3
Primary Voltage	kV	33
Secondary Voltage	kV	0,8/0,8
Type of tap changer		On-load
Vector Group		Dy11-y11
Frequency	Hz	50
Half-through impedance Uk (HV/LV1), Uk (HV/LV2)	%	8,2
Half-through impedance Uk (LV1/LV2)	%	16
No-load losses	kW	5,7
Load losses at rated power HV to LV	kW	29

The inverter employed in this configuration is the string inverter which has a nominal rated power of 330 kW at cosφ = 1, under nominal voltage conditions and an ambient temperature of 30°C.

The inverter is capable of supplying both active and reactive power to the grid, with reactive power support available in both lagging and leading operating modes. Furthermore, the string inverter supports reactive power provision even at zero active power output.

The maximum output power of the string inverter depends on the inverter terminal voltage. When operating at voltages above the nominal value, the inverter can deliver apparent power exceeding its rated capacity, whereas at voltages below nominal, the available power output is reduced.

The main 400/33/33 kV, 620 MVA transformers and the 400 kV PoC busbar are interconnected using 400 kV, 800 mm² XPLE single-core cables. The 33 kV side of the main transformers is connected to the main 33 kV busbar through five 33 kV, 630 mm² XPLE single-core cables.

PV blocks are connected to the 33 kV switchgear using 33 kV, 500 mm² underground aluminium XPLE cables, while internal connections between PV blocks are implemented with 240 mm² underground aluminium XPLE cables. Low-voltage connections between the PV inverters and the inverter transformers are realized using 0.8 kV underground aluminium XPLE cables with a cross-sectional area of 300 mm².

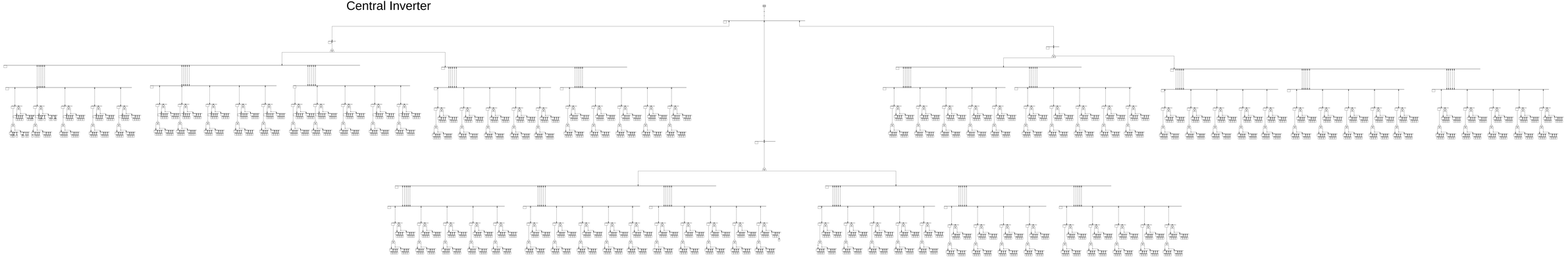
The parameters of all the aforementioned cables are summarized in Table 11 below.

Table 11 - Cable Parameters

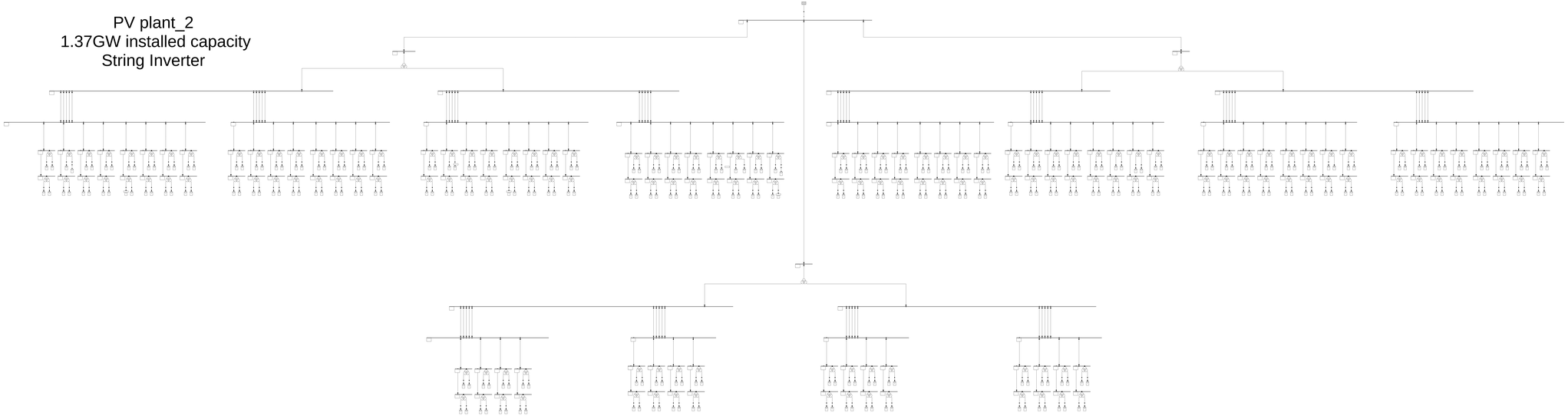
Cross section [mm2]	Voltage	AC resistance [Ohm/km]	Reactance [Ohm/km]	Capacitance [uF/km]	B [s/km]	Current rating [kA]	Rzero [Ohm/km]	Xzero [Ohm/km]
1x800C	400kV	0.0309	0.2540	0.1500	4.71E-05	0.9790	0.0943	0.0969
1x630C	33kV	0.0398	0.1106	0.3420	1.07E-04	0.728	0.1708	0.0583
1x500Al	33kV	0.0794	0.1137	0.3100	9.74E-05	0.5230	0.1709	0.0578
3x240Al	33kV	0.1610	0.1109	0.2440	7.67E-05	0.3380	0.9701	0.0498
3x300Al	0.8kV	0.1310	0.0654	0.6160	1.935E-04	0.2540	0.7893	0.0282

APPENDIX B – LAYOUT OF THE PV PLANTS

PV plant_1
1.39GW installed capacity
Central Inverter



PV plant_2
1.37GW installed capacity
String Inverter



CONTACT US

Go2power consulting

Cara Uroša 8a, Belgrade 11000 Serbia

Tel: +381 63 470 660

info@go2power.eu