COMMISSIONING AND TRIAL OPERATION OF PHOTOVOLTAIC POWER PLANT KANFANAR (999 kW)

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ABSTRACT

The paper analyses the impact of the photovoltaic power plant to the grid by analyzing the response of the power plant in extreme situations in the grid, performed in predefined real-time tests during the trial operation of power plant.

INTRODUCTION

Photovoltaic (PV) power plant Kanfanar (999 kW) is the first PV power plant in Croatia connected to middle voltage (20 kV) national distribution grid and is also currently the largest self-standing photovoltaic power plant in Croatia.

Power plant consists of 76 inverters, rated power of 12 kW, which are through low voltage (LV) wiring connected to block transformer (0,4/20 kV) of PV plant, and further via middle voltage (MV) cable to the point of common coupling (PCC) in the distribution grid (Figure 1).

The commissioning and testing protocol was based on the PV plant and grid connection project documentation, electrical equipment documentation and on experiences of Distribution System Operator (DSO). Commissioning and testing in trial operation have lasted for 5 days and during those days various tests have been performed. Tests included the process of synchronization and the process of disconnection of PV plant, and PV plant's response to a fault in distribution grid and a fault in PV plant itself.

The most interesting tests performed in trial operation are:

- **Response of PV plant to real fault (two-pole short circuit) in the MV distribution grid**;
- **Anti-islanding test of PV plant**.

MEASURNIG POINT

During the tests electrical transients were recorded at three measuring points (MP), according to Figure 1:

MP1 – 20 kV feeder in supply substation (110/20 kV);

MP2 – 20 kV bus at PCC;

MP3 – 0,4 kV bus at LV distribution board in PV plant at which 14 inverters are connected.

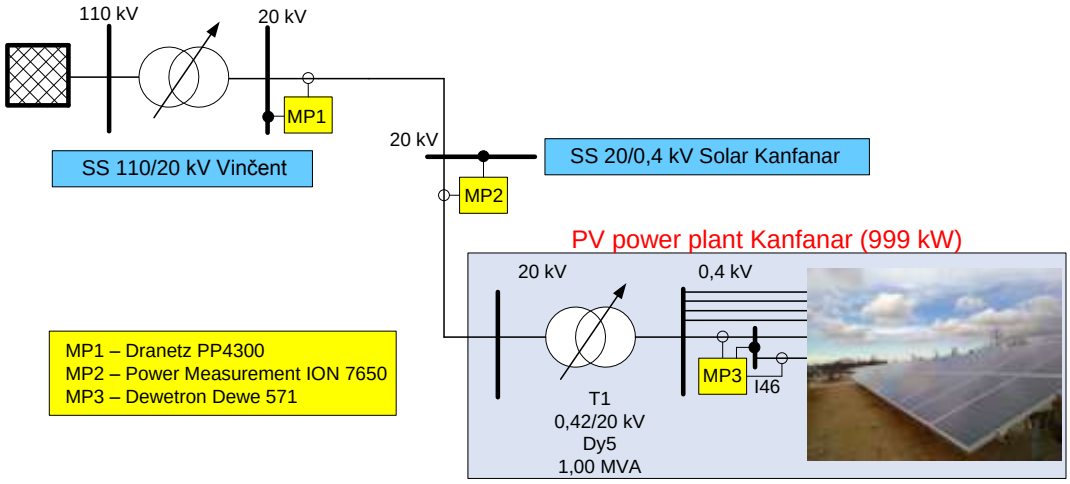

Figure 1 Metering points in power plant and in surrounding distribution grid

RESPONSE OF PV PLANT AT THE OCCURRENCE OF A FAULT IN THE GRID

In case of fault (short circuit) in the grid, PV plant should disconnect in order to stop feeding fault location and not to increase fault current (it is a DSO's requirement). The plant should also disconnect in case of temporary failure, when grid is passing through autoreclosure (AR) procedure cycle. The goal of this test was to determine functionality of respective protection.

Test of PV plant response to temporary fault **was performed in real conditions** by connecting the grid to the malfunctioned part of grid (two phases short circuited), while the plant was synchronized to the grid and while the majority of local consumers was disconnected (for security reasons). Two pole short

circuit was performed in the distribution overhead line, while the supply of electricity was cut off, by connecting two phases by Cu wire 1,5 mm^2. Test was performed two times.

Figure 2 and Figure 3 show the results at the MP3. As the figures show at the time of fault appearance it comes to an immediate decrease of voltage in malfunctioned phases. This leads to disconnection of PV plant within 200 ms by action of undervoltage protection (U<) at inverters. Overcurrent protection of respective feeder in supply substation trips 600 ms after appearance of fault. Considering the temporary character of failure (cooper wire melts due to thermal stress during short circuit, $I_{SC} \cong 1000$ A) after the period of disconnection of supply feeder of 400 ms, the three pole reclosing procedure reconnects the supply feeder and synchronization process of PV plant starts again.

Voltage protection (U<, U>) is selectively adjusted in two degrees. First degree is at inverters and second degree is at circuit breaker (CB) at PCC (in the grid). Selectivity is achieved if temporary failure leads to tripping voltage protection at inverters while voltage protection of CB at PCC doesn't trip. It has been confirmed by respective test.

In case of permanent failure in the grid, undervoltage protection acts both on inverters and on CB at PCC. Therefore, after the permanent fault has been eliminated, or new topology of the grid has been established, DSO has to remotely reconnect the PCC (CB) in order to enable synchronization process of PV plant.

In case of three-pole short circuit in distribution grid response of PV pant will be the same as in case of two-pole short circuit (except of short circuit near supply substation when feeder protection trips immediately) because in that case, at occurrence of fault, voltage decreases in all three phases.

In case of phase to earth fault (while grid is grounded by parallel connected resistor and damper) PV plant does not disconnect because voltages at LV side of PV plant's block transformer (voltages at inverters) stay unaffected due to earth fault in MV grid. In that case PV plant disconnects by action of earth-fault protection of feeder in supply substation.

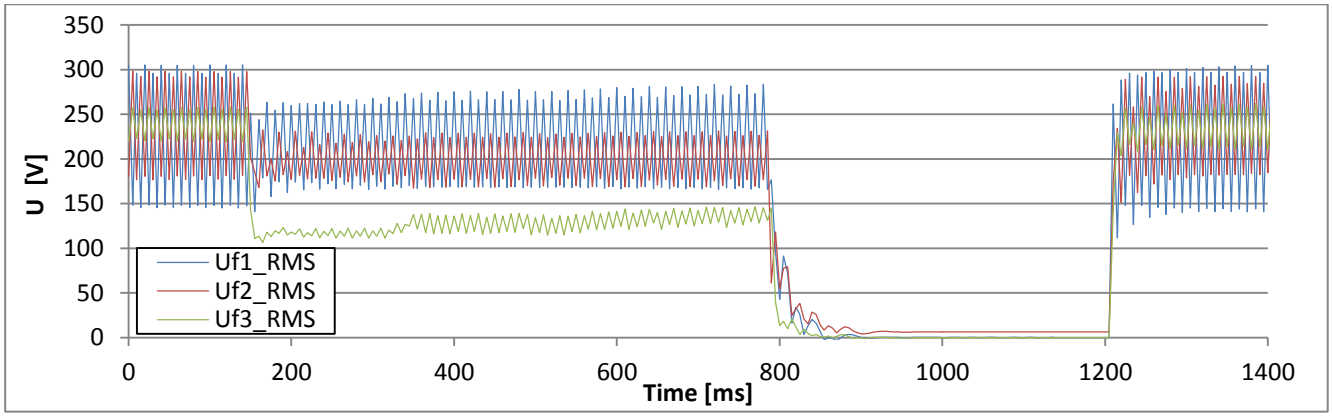

Figure 2 RMS voltages at MP3 while the grid is passing through AR

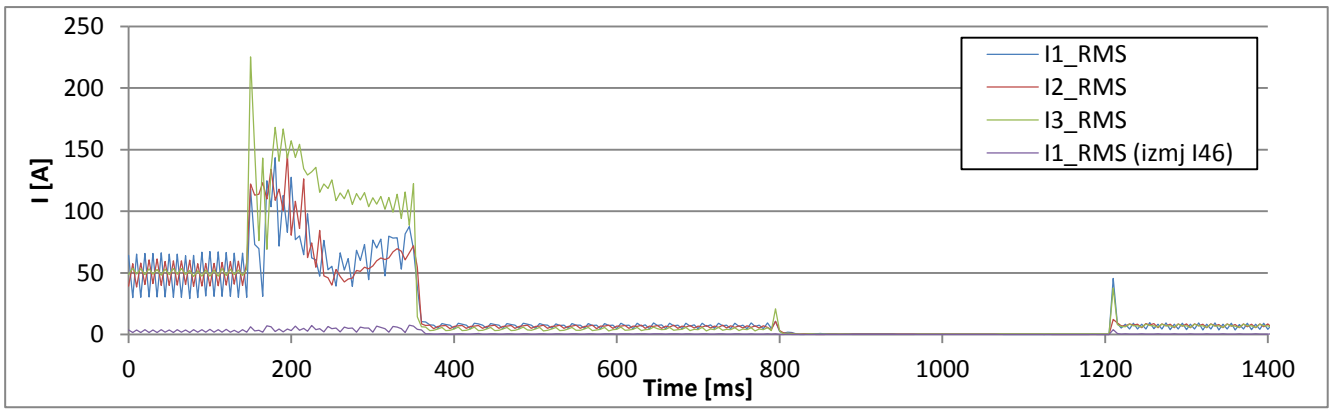

Figure 3 RMS currents at MP3 while the grid is passing through AR

ANTI-ISLANDING TEST

In the context of PV plant island operation is undesirable and prohibited state in which distributed source remains to supply isolated part of the grid, although this part of the grid is in supply substation disconnected from the rest of electric power system. That operating state can cause a range of hazards because voltages and frequency of isolated part of grid in island operation are no longer linked (synchronized) with voltages and frequency of

electric power system, and part of grid in island operation loses the stability granted by the system. Taking that into account, during the re-establishment of normal grid topology, high transient currents may arise.
However, the fact that the DSO's personnel are not aware, and do not expect that the isolated part of the grid (disconnected in supply substation) is still powered by the distribution source is even more dangerous.

Anti-islanding protection of PV plant Kanfanar

Anti-islanding protection of PV plant is realized locally, at inverters, which have implemented passive and active anti-islanding protection methods.

Passive anti-islanding protection

Passive method, which is normally used to detect disturbances in the grid, is based on measurement of basic system parameters (voltages and frequency) which may vary significantly when part of the grid turns to island operation. In case any of system parameters exceeds allowable values voltage (U<, U>), and/or frequency (f<, f>) protection trips and PV plant disconnects and stops to supply isolated part of grid.
Power flow in distribution grid with PV plant connected is shown at Figure 4. Figure shows the case in grid when production of PV plant is insufficient to supply total consumption of feeder, so the rest of the load $\Delta P + \mathrm{j}\Delta Q$ is supplied form the rest of electric power system. If this part of the grid turns into island mode (by disconnecting the feeder in supply substation), the change of system parameters will occur.

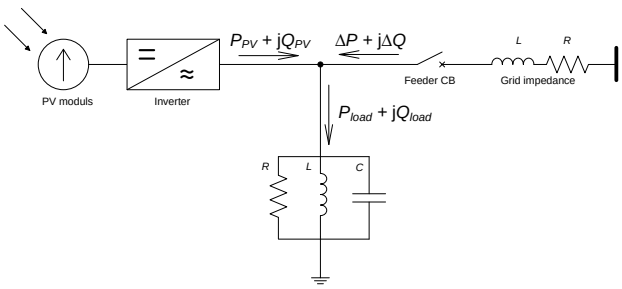

Figure 4 Power flow in grid with PV plant connected

Since inverters always operate in maximum power point (PV plant can be considered as a source of constant power) and cannot compensate real power ΔP which was previously supplied by supply substation, new power balance will be established at lower voltage, which leads to U< trip.
Difference in reactive power ΔQ causes increase of frequency in isolated part of grid. Inverters tends to keep $\cos\varphi = 1$ (it is a usual set up value) so inverters seek for resonant frequency to eliminate flow of reactive power in isolated part of grid, which leads to f> trip.
In case $\Delta P < 0$ power balance in separated part of grid is established at higher voltage, as well as $\Delta Q < 0$ leads to establishing of power balance at lower frequency.
Passive anti-islanding detection method is very practical and very reliable in most cases. However, there are circumstances in grid when **non-detectable zone (NDZ)** occurs. NDZ occurs if ΔP and ΔQ are relatively small, or if there is $P_{PV} + jQ_{PV} \cong P_{load} + jQ_{load}$. Changes of system parameters at the time of disconnection part of the grid with PV plant from the rest of electric power system are no longer sufficient for tripping neither voltages, nor frequency protection, so the island operation of PV plant and part of grid is established despite the passive anti-islanding protection.

Active anti-islanding protection

Since there are circumstances in the grid in which passive anti-islanding method is inadequate to detect island operation, inverters have also implemented active anti-islanding detection method. For active anti-islanding detection inverter usually injects a specific perturbation in one of the three output current parameters (amplitude, frequency or phase angle) and tracks voltage response to injected perturbation.
In PV plant Kanfanar inverters increase current amplitude for 10% every 25 periods (500 ms), and decrease current amplitude for 20% in next period and track voltage response on changes of currents $\mathrm{d}v/\mathrm{d}i_{inv}$. This active anti-islanding detection method is called **Impedance Measurement method**.
In case of PV plant connected to the electric power system, that changes (perturbation) of inverter's output current will have no practical effect on grid voltage due to impedance of electric power system is close to zero ($Z_{EPS} \cong 0\ \Omega$). However, if part of grid (feeder) with PV plant separates from the rest of the system, that part of grid now has some real impedance ($Z_F > 0\ \Omega$) consisting of load impedance and grid impedance. In this simplified case it can be considered that impedance of separated part of grid is constant, although, in reality, load impedance is voltage depended. However, if in separated part of grid in island operation occurs change of current, then, due to grid impedance, according to Ohm's law, proportional change of voltage occurs, so island operation is detected due to change of $\mathrm{d}v/\mathrm{d}i_{inv}$.
This method if very reliable and, theoretically, it has an extremely small NDZ, but **only in case if PV plant has single inverter**. However, if the plant is built with multiple inverters, as it is case in PV plant Kanfanar (76 inverters), effectiveness of impedance methods decreases because inverters do not inject current perturbations synchronously. The reason is that as more inverters are added to the island, the amount of variation introduced by each inverter into the total current being generated by all inverters is reduced, and eventually the variation becomes so small that the change $\mathrm{d}v/\mathrm{d}i_{inv}$ becomes undetectable. In addition, it is possible that unsynchronized current perturbations cause destructive interference and thus change $\mathrm{d}v/\mathrm{d}i_{inv}$ becomes even more unnoticeable.
Therefore, for adequate and reliable anti-islanding protection in multi-inverter case using Impedance

Measurement Method, it is necessary that the inverter's perturbations are synchronized, but it is not the case in PV plant Kanfanar.

Anti-islanding test

Anti-islanding test was performed by creating the marginal real condition in part of the grid - power balance in the point of disconnection in the grid (production of PV plant equal to consumption of corresponding part of grid (feeder)). During the test, in state of power balance (obtained by reducing the production of PV plant to meet the actual consumption of the feeder), when current of feeder in supply substation (at MP1) achieved minimal value (close to 0 A) the feeder was deliberately disconnected creating the state of island operation of PV plant with part of the grid.

Since PV plant produces pure real power, and the feeder consumes certain reactive power which cannot be influenced, it is not possible to achieve absolute power balance, hence the current at MP1 was not exactly 0 A. Moreover, the measurements accuracy low values of current is very questionable because measurement is performed through current transformers which's core is adjusted to measure high fault currents.

Therefore test was performed four times and each time electrical transients and duration time were measured during the island operation. Figure 5 and Figure 6 show the result for case of island operation that lasted the longest.

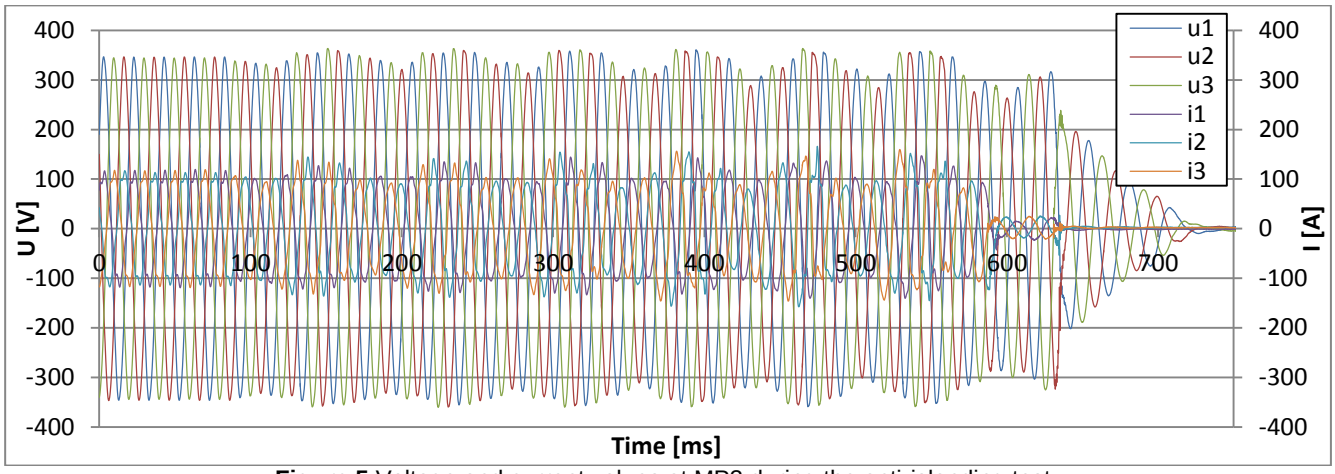

Figure 5 Voltage and current values at MP3 during the anti-islanding test

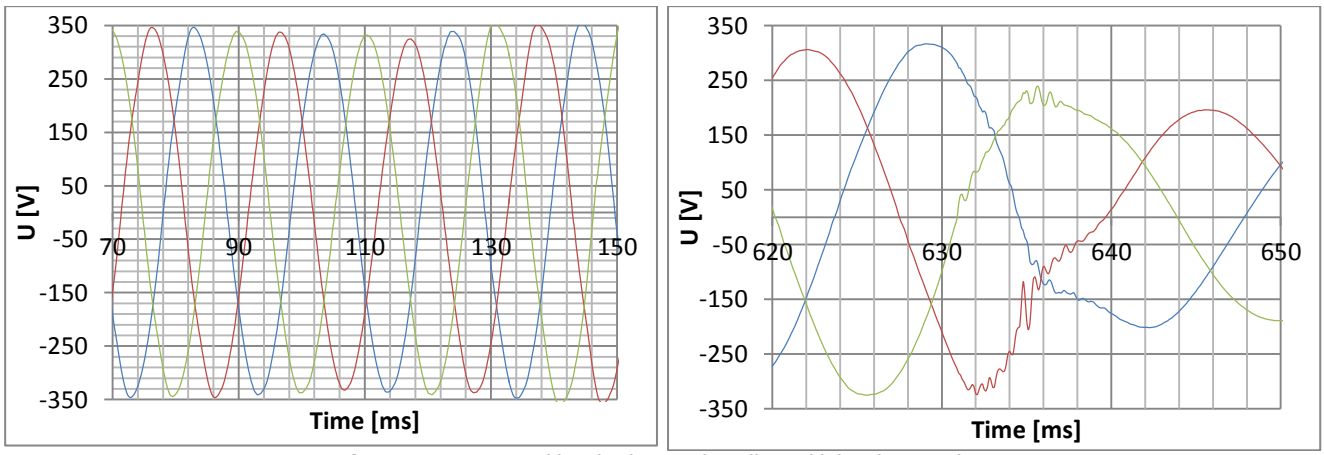

Figure 6 Moment of beginning and ending of island operation

Figure 5 and Figure 6 show that island operation started at 90th ms and ended at 632nd ms, so the total time of island operation was 542 ms. Since island operation lasted more than 500 ms (500 ms is maximal period for Impedance Measurement Method to detect island operation) test results proved that Impedance Measurement Method is not adequate for multi inverter power plants.

Furthermore figures show that at the moment of turning into island operation there is an immediate voltage decrease meaning that real power production of PV plant was lower than feeder consumption ($P_{PV} < P_{load}$). However, the production and consumption imbalance was not sufficient for U< trip because power balance was established at voltage that was within allowable range. Although current, and thus voltage, oscillates in island operation, voltage does not exceed allowable range, at any moment. Even if does, that condition does not last

long enough for voltage trip (100 ms for U>, and 200 ms for U<). In such conditions, considering only real power flow, island operation would last till occurrence of imbalance – changes in production or consumption in part of grid in island operation.

However, since PV plant produces pure real power, and, as it will be shown later, part of grid in island operation produce reactive power (grid is overcompensated, $\Delta Q < 0$), the difference in reactive power ΔQ causes f< trip, as it is confirmed at Figure 7.

Figure 7 shows exact voltage period at the time of inverter I46 disconnection. This period lasts for 21,6 ms, showing that in this moment frequency is 45,8 Hz which leads to f< trip. The same situation occurs at all inverters which in further period of 40 ms randomly disconnects from the grid.

After all inverters are disconnected, at part of grid which was previously in island operation occurs damped oscillations at resonant frequency around 37 Hz. This confirms that at frequency of 50 Hz that part of grid produces reactive power (capacitive character). This is also confirmed at Figure 7 because current precedes voltage.

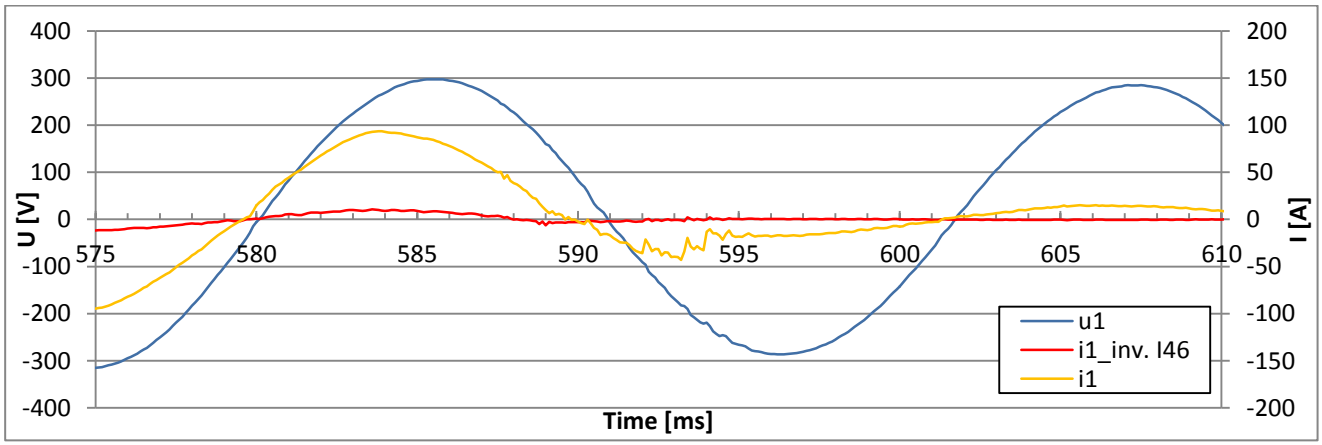

Figure 7 Electrical transients at time of disconnection of inverter I46

Tests results shows that island operation which was created deliberately didn't maintain significant time. However, the tests confirmed the opinion that effectiveness of Impedance Measurement Method decreases in the multi-inverter case, and one cannot conclude in which time, if ever, island operation would be detected. In the conditions existed in grid during tests, island operation was detected by passive method. In such conditions long duration of island operation is not possible because capacitive character of grid causes decrease of frequency bellow allowable range.

However, during tests the grid was not set up in normal topology, and with the increase of load capacitive character of grid fades away so the grid character gradually becomes inductive, leading to natural pure active feeder load (cosφ=1), one cannot guarantee that long lasting island operation is not possible. Moreover, in [3] and [4], it is shown that with standard U-f protection settings, for the worst case grid configuration (quality factor of RLC load is $Q = 2{,}5$) NDZ is determined with (1) and (2) which is far from negligible.

$$-17{,}36\% \leq \frac{\Delta P}{P_{PV}} \leq 29{,}13\% \qquad (1)$$

$$-5{,}94\% \leq \frac{\Delta Q}{P_{PV}} \leq 4{,}11\% \qquad (2)$$

CONCLUSION

The results of the tests during the trial operation gave new insights into the real interaction of power plant and grid, pointing out possible problems that could not be detected otherwise. So the tests provide assurance (both to power plant and to DSO) in adequate parallel operation of a power plant with the grid in those states of the grid for which the tests confirmed the appropriate response of the power plant. These findings emphasize the importance of testing during the trial operation of each power plant.

LITERATURE

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