Development of an innovative grid ancillary service for PV installations: Methodology, Communication Issues and Experimental Results

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In high Renewable Energy Sources (RES) penetration cases and especially whenever local grids are considered, the absence of coordination between RES production and demand includes the risk of reduced reliability of power supply to the consumers. In this paper, an innovative, cost-effective and easy to install technology is introduced that allows PV sun-tracking systems to regulate their actual energy production according to the network demands instead of relying on the inverters to manage the excessive energy. This method is suitable for existing applications where energy storage is not possible. In addition, a main advantage of the proposed method is that it protects the PV panels from high temperatures when network loads permits, expanding thus the life span of a system. This technology utilizes control-automation and communication tools, to adjust the PV power production of distributed sources with respect to the needs of the consumers as well as to the technical and economic requirements of the electricity grid and the power market. The main idea is to use the sun-tracking system, i.e. by changing the position of slave trackers, for achieving maximum power and to determine the unserved power, so that enables charging and market integration potential. The system can be adopted to almost all sun-tracking systems, whereas the signal transmission towards the PV system is accomplished by the newly-introduced and the cost-effective Digital Audio Broadcasting (DAB) energy data transmission protocol.

Introduction

In many European Union (EU) countries, the laws allow premium access to the grid for RES. Consequently, weather-dependent RES, such as PV-plants and wind-farms, operate at their maximum possible outputs whenever technically possible and therefore do not follow the variation of energy consumption. In high RES penetration cases and especially whenever local grids (e.g. microgrids) or isolated energy networks (e.g. islands) are considered, the above operational principles and trends include the risk of reduced reliability of power supply to the consumers.

For example, at many rural and low-populated areas in Greece, the power produced by Distributed Generators (DGs) at specific hours during a day exceeds the local demand, leading to local overvoltage and DGs outages.

Therefore, the ancillary services that could be provided by the supply-side and the demand-side are expected to increase the value of the future smart grid [1-6]. Load levelling and demand-side management are extensively used in general to provide services like Voltage regulation and energy management for isolated microgrids [2, 6, 7].

Furthermore, increasing penetration of DGs has brought new challenges for network operators to ensure real-time energy balancing. The operation of DGs is optimized using the concept of local energy balancing and ancillary services (ASs) [8]. Heating, Ventilation, Air Conditioning (HVAC) systems can provide ancillary services to the distribution grid without sacrificing occupant comfort [9]. Community microgrids are also capable of providing ancillary services to the main distribution grid [10].

In [11] the authors propose a technique that is applied in stationary PV systems and uses relays to control the output of the PV strings and thus the output power of the whole PV plant. However, the system could not estimate a-priori the reduction or increase of the output power and could not estimate the lost power. Therefore, the market integration potential was limited.

In [23, 26, 27], controlling the network power by storing the power surplus for later use is analysed. This is one method to control grid power quality and voltage rise.

In [24, 25] a method to accomplish voltage regulation using the injection of reactive power into the grid by using the PV inverters is presented. The new PV inverters are required to have the capability to provide a static amount of reactive power. However, the amount of reactive power that can be injected appears to be limited for the MV and LV distribution grid needs, such as the LV transformer.

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In this paper, the authors propose an adaptive system that uses the sun-tracking system of PV plants, for achieving not the maximum possible output power but the required one. It basically bypasses the main tracker control and changes the position of slave trackers and can be adapted easily to all existing trackers.

A power measuring device is installed at the output of each inverter, for measuring the power and energy produced by each PV segment and these measurements are compared with the values required by the network at that time.

The network demand is assumed to be sent periodically by the distribution administrator and the system adapts the PV station's power to the most recent demand value. The purpose of the proposed system is to adapt to long term variations between demand and production and not to temporary high frequency variations.

After checking all the trackers, the system changes the position only of the slave trackers, initially by moving them a few steps to the east and then by lagging behind the master trackers according to the desired reduced output power. The main challenge is to be able to modify the position of the slave trackers without affecting the main tracking system that operates the PV system.

When the proposed add-on system receives a message from the network administrator that reduced power is required, it takes over the control of the slave trackers and shifts them from their original position until the required power level is achieved. It operation is transparent to the original main tracking system which continues to follow the maximum power position. When the PVs reach the desired power level, control is returned to the main tracker but the panels remain shifted the add-on tracker knows the real position of the panels and can adjust their direction when needed.

An important goal for the proposed system is to avoid operating the PVs at maximum temperature mode when possible, in order to prolong their operational life span. Therefore, the control mechanism is trying to achieve the required reduced power by shifting the entire assembly instead of shifting only some of the PV units.

Although the power produced by each panel unit is monitored and it is possible to shift only one or selected PV panels, the presented algorithm shifts all the panels by the same angle until the total power is reduced to the desired level.

This system is mainly intended to adapt to significant network voltage variations, especially in areas where power cannot be otherwise regulated and not to temporal minute variations of power demand.

In addition to the main feature of the proposed system (producing only the required power and energy at any time) other advantages of the proposed system are that:

(a) It can be addressed by cost-effective communication methods, such as ripple control that all substations have and the newly-introduced DAB signalling.

(b) It is much more cost-effective than replacing the old inverters of existing PV power plants with the new ones that obtain ancillary services options [12-16].

The paper is structured as follows: In the following section, a detailed description of the proposed control system for the ancillary service of PV plants with sun-tracking systems is presented, together with financial details. Section 2 analyses an existing PV plant with sun-tracking systems where the control system was applied and tested. In Section 3 actual results are shown and in Section 4, the conclusions are outlined.

Proposed control system for the ancillary service of PV plants with sun-tracking systems

Description of the control infrastructure

In a common distribution network, on the 20 KV lines that supply the loads, there are also distributed renewable energy sources (RES-DER), with varying energy production. This usually leads to increased or decreased voltage on some of the line loads through the day. The solution of partial energy storage is very costly and difficult to implement because of the dynamic behaviour of the above system of loads and energy production on the line. Therefore, the authors created a system for controlling the generated energy to match the line loads. The control infrastructure design is based on the following concept: In case a distribution transformer has reached saturation, a command is sent to the PV power plant that supplies that transformer informing -that power output must be reduced by a certain percentage. The network administrator may issue such signals to individual plants or to groups of PV plants so that the actual production matches the demand According to the command, the proposed control system regulates its energy production, while still tracking the maximum power potential in order to be able to respond to increased loads, to achieve the production that the network requires.

The operation is done in the following way: When the proposed system receives the message, it starts causing diversion tracking, except from the master tracker, which continues to follow the sun optimally. The drift of the secondary trackers is usually to the east direction (opposite of the master tracker). Thus, the slave trackers lag behind the master trackers, in such an angle that the required output power can be achieved. The control algorithm is a Perturb and Observe (P&O) algorithm: For example, after receiving the command, the P&O algorithm forces the ancillary service system to take over and depending on the desired output power, it may shift the slave trackers e.g. by 6 tracking steps to the east and then transfer the control again to the existing tracking system. A controller measures continuously the output of the master inverter and it compares it with the production of the slave inverters. If the controller detects that the power required by the distribution network is lower than the power provided by the panels, it overrides the master tracker and moves the slaves trackers step by step to east until the proper power reduction is achieved. The controller keeps track of the number of steps that the panels have been shifted and the exactly position of the master and slave trackers. When the panels reach the desired shifted position, the controller gives again control to the main tracking system. The main controller continues tracking all trackers and is unaware of shift introduced by the additional controller, which may take over control again in the same manner, in case it detects wrong output power. The reason for that system's attitude is the flexibility potential: For example it can easily reduce the energy production more, if requested. So the processor can always adjust the output power compared to the power that could be produced.

Finer power adjustment can be achieved by changing the position of only one or selected slave trackers. Most PV panel trackers can rotate the PV assemblies by more than 90 degrees, therefore the power reduction can be very significant. In the extreme case where the reduced power is still higher than the demand, selected PV groups can be completely disconnected from the system.

If the network distribution requires more power then the additional controller reroutes slave trackers to their original position and maximum power output is restored. When the power reduction command ends, the add-on board shifts the slave trackers to the same position as the master tracker and returns control to the excising tracking system. In all cases the additional controller keeps track of the slaves position and can adjust the shift steps so that the panels' output matches the load required by the distribution network without affecting the original master tracking system.

When power reduction commands stop, the board takes control of slave trackers. It shifts them to the same position as the master tracker by isolating inputs and outputs of the excising tracking system. As a result, all trackers now have the same position and continuous tracking with main tracking system.

In order to realize the above integrity operations, the following recording measurements are needed. First of all, power production of the pilot tracker's inverter is recorded. Current and voltage sensors measure max power that all inverters produce. Then a second meter measures the controlled decreased power production of the other trackers' inverters. The additional controller calculates the produced energy and issues commands to slave tracking systems for more or less power production, according to the needs of the distribution system. Finally, a third measuring device records the total power delivered from the power plant. This way, the power and energy that should have been delivered to the network is calculated. This enables the network distribution system to know, the actual power availability of a system which operates in reduced power mode. Finally, a device that collects the inverters' output data is used. So the system has the advantage of online detailed monitoring. The authors' goal is to adapt the system to all existing trackers, the majority of which are controlled by PLC using a time algorithm or sensors.

The P&O algorithm is presented in Fig. 1, and the block-diagram of the proposed control algorithm is shown in Fig.2. The block diagrams of the board and its connection to the existing sun-tracking system are presented in Fig. 3. In Fig. 4, a photograph of a prototype system is shown.

Fig. 1. The P&O algorithm block diagram

Fig. 2. The authors tracking control algorithm block diagram

Fig. 3. (a) The block diagram of the modules of the proposed control system, (b) The block diagram of the connection of the board to the sun-tracking system. The transfer of control between the two systems is obvious

Fig. 4. Photograph of the modules and boards.

Cost analysis and advantages

It is well-known that solving power quality problems will give the opportunity for integration of more renewable energy sources [2-3]. If energy production on a distribution line is controlled by the network administrator when necessary, the DER capacity of the line will be increased. Such a solution is much more cost-effective than energy storage solutions. The proposed system is designed to be installed in parallel to the existing control system. It needs extra power measuring systems for each inverter which is on board the proposed system, except from the current and voltage sensors. The readings of the inputs and outputs of the existing control system are acquired through mini relays, to achieve isolation. These mini relays do not allow the input data to reach the PLC and do not allow the output command of the PLC to reach the slave tracker. So only the proposed system receives the slave tracker input data, in order to control the slaves' behaviour and isolate the PLC output. The most expensive part is the command board and the transceiver that is used to communicate with the Distribution System Operator through the ripple control telegraph, which sends signals through power lines to specified parts of the network. The proposed system includes 3 additional power monitoring units collecting data that can be sent to the Network administrator via internet connection or with a DAB signaling device.

In the implemented system, the commands are transmitted by utilizing ripple control and an Internet connection. However, the cost is significantly reduced if the signal is transmitted to the PV plant through the newly introduced DAB energy data communication protocol [17-19], that is described in more detail in the following section.

The advantages of the new data communications system are:

- The proposed system can be addressed by cost-effective communication methods, such as ripple control and the newly-introduced DAB signalling.

- The proposed system is especially beneficial for existing PV power installations, since it is much more cost-effective than replacing the old inverters of existing PV power plants with the new ones that obtain ancillary services options.
- The proposed system can cause power reduction as much as the network administrator asks from RES. The advantage is that the power reduction can be measured very accurately. Firstly the administrator knows the power that it can be available for the grid at any time that it is asked. Secondly the power reduction can be measured and the owners of the power plants can be rewarded for the services that they provide for network operation.
- When we have high energy production energy areas far from the main transformer and the local loads are very poor so reactive power is negligible, inverters cannot regulate voltage increases, there that system can avoid inverters to shut done from overvoltage. Only the hours that we have no loads and big energy production.

PV plant with sun-tracking system for testing

The proposed system has been tested on many types of trackers. The biggest difficulties encountered while applying the idea appeared with trackers where the movement is controlled by a linear gearbox. For the needs of this study, the proposed system was installed in a power plant which has five trackers with installed power of 20 kW each. The construction of each tracker is as follows: The panels on idle mode are in the direction north to south and are located in relation to the level of ground, on a slope of 20^o. Six panels are grouped together on a frame. 14 of those frames constitute one tracker. Each frame is mounted on a metal shaft part of the tracker which can perform a semi-circular motion in the East-West direction. Each bracket of the frame is held in a linear axis. Each tracker has the same number of panels and therefore the same installed capacity. In summary, there are 5 similar trackers that are running the same route in one common PV power plant. A single pilot tracker is used as reference point, to calculate the output power that the slave trackers should obtain. The proposed system then calculates and controls the power that is produced by the power plant. In Fig.5, a photograph of the pilot PV plant is shown, taken during the ancillary service operation and it is obvious that the slave trackers (rear) have different angle than the master tracker (front).

Fig. 5. The pilot PV plant. The photograph is taken during the ancillary service operation and it is obvious that the slave trackers (rear) have different angle than the master tracker (front).

Experimental results

In most of the sun-tracking systems, a single base follows the sun optimally. In the proposed system, after receiving a command for power change, this single base keeps following the sun optimally, whereas the others are turning to the east in such a relative angle to the master-tracker base, that the plant can achieve the desired power production. This control system is also important, in order to calculate the unused energy.

In Fig. 6, two typical PV power production curves of the pilot installation are shown, after applying a command for 10 % of power reduction. The dotted line is the actual power production and the continuous line is the calculated output power that should have been produced, if no ancillary service was applied.

Fig. 6. Power curves for operation of the pilot PV plant, after a command for 10 % of power reduction

In Fig. 7, the output power of the master tracker and of one slave tracker is shown, in a more complex command that requests power reduction of 20 %, 5 % and 10 % in sequence.

Fig. 7. Power curves of the master-tracker and one slave-tracker for a gradual power reduction command.

Table 1 presents the exact time of signal generation by the DSO, the desired power reduction (10 %) and the achieved power reduction (10-minutes average value).

As was stated earlier in addition to dynamically adapting the PV production to the required loads of the distribution network, the proposed system reduces the operating temperature of the PV panels, as they do not operate continuously at maximum capacity.

Table 2 shows the temperatures of two PV sectors, one operating in maximum capacity and another operating in reduced capacity as dictated by the distribution network. A significant temperature difference of 2.5 to 3.0 degrees C is observed. Fig**.** 8 shows the panel temperature differences caused by the proposed add-on tracker shift.

Fig. 8. Temperature difference caused by tracker shift

As has been stated earlier, one major advantage of the proposed system is that it does not require energy storage facilities, which can be very expensive. However by comparing the power of the master tracker and the shifted slaves' trackers, the available excessive energy can be calculated at any time and can be partially or fully provided to the distribution network if needed.

Table 3 contains experimental data of energy produced by the master and a slave tracker that is on reduced power mode and Fig. 9 shows graphically the "excessive" energy that is available. The distribution network administrator can keep track of this available excessive power and can estimate the "stored" energy that can be made immediately available to the distribution by cancelling the power reduction mode.

Fig.9 Power reduction in experimental setup

Table 4 shows how power output can be adjusted to various network demands and the angle by which the add-on controller shifts the slave trackers in order to achieve the required power reduction. Figure 10 shows graphically the resulting power levels of the experimental installations for various reduced power requests

Fig.10 Output Power Reduction and Shift angle of slave trackers

Conclusion

In this paper, an innovative, cost-effective and easy to install technology is introduced that allows PV sun-tracking systems to regulate their production according to the demand. The main idea is to use the sun-tracking system, i.e. by changing the position of slave trackers, for achieving not the maximum possible power output but the desired one. The proposed system is also able to calculate the maximum power and measure the lost power, therefore enabling charging and market integration potential. The system can be adjusted to almost all sun-tracking systems, whereas the signal transmission towards the PV system can be accomplished by the newly-introduced in this paper Digital Audio Broadcasting (DAB) energy data transmission protocol. Additional advantages of the proposed system are that:

(a) It can be addressed by cost-effective communication methods, such as ripple control and the newly-introduced DAB signalling.

(b) It is much more cost-effective than replacing the old inverters of existing PV power plants with new ones that obtain ancillary services options.

(c) In a distribution network line with the proposed system, the voltage control and the powers quality along the MV line is on the administrators' supervision and surveillance.

(d) It protects panels from unnecessary expose to higher temperature that may lead to production problems in the future.

The proposed system was installed on a 100 kW nominal capacity PV power plant. The results show that the desired power regulation can be achieved with great accuracy and with minimum time delay. The described procedure, not only relieves the local distribution grid from the strain during peak production periods, but can also contribute to cost-effective operation of the grid. Moreover, it can also contribute to increased penetration of PV power plants in an area, since it regulates energy peaks from RES.

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Table 1 Desired and achieved power reduction and diversion angle for the two days of pilot operation of the PV plant

Time	Output Power without ancillary service (W)	Output power with active ancillary system service (W)	Actual power reduction
17/3/2017 11:20	79248	79248	0,00%
17/3/2017 11:30	80159	80159	0,00%
17/3/2017 11:40	78526	78526	0,00%
17/3/2017 11:50	79708	79708	0,00%
17/3/2017 12:00	79852	71866	10,00%
17/3/2017 12:10	79206	71285	10,00%
17/3/2017 12:20	78704	70762	10,09%
17/3/2017 12:30	79284	71284	10,09%
17/3/2017 12:40	79488	71467	10,09%
17/3/2017 12:50	79692	71651	10,09%
17/3/2017 13:00	80294	72264	10,00%
17/3/2017 13:10	80503	72452	10,00%
17/3/2017 13:20	79955	71959	10,00%
17/3/2017 13:30	77904	69903	10,27%
17/3/2017 13:40	79357	71207	10,27%
17/3/2017 13:50	78904	70800	10,27%
17/3/2017 14:00	79267	71126	10,27%
17/3/2017 14:10	79191	71058	10,27%
17/3/2017 14:20	79728	71755	10,00%
17/3/2017 14:30	78789	70910	10,00%
17/3/2017 14:40	78753	78753	0,00%
17/3/2017 14:50	77836	77836	0,00%
17/3/2017 15:00	78321	78321	0,00%
17/3/2017 15:10	78018	78018	0,00%

Table 2 Temperature differences caused by tracker shift

Time	Temperature of shift tracker (C)	Temperature of non shift tracker (C)
10:00	40.78	40.88
10:15	42.90	42.90
10:30	45.01	45.01
10:45	47.02	47.08
11:00	47.27	47.30
11:15	48.41	48.48
11:30	50.80	50.85
11:45	52.47	52.51
12:00	54.00	54.05
12:15	54.89	54.99
12:30	54.01	55.15
12:45	53.22	56.69
13:00	53.67	57.45
13:15	54.01	58.13
13:30	52.55	55.86
13:45	51.65	54.75
14:00	51.25	54.12
14:15	51.72	54.85
14:30	51.98	54.48
14:45	51.24	54.01
15:00	52.01	55.08
15:15	53.31	53.88
15:30	53.17	53.17

Table 3 Energy storage by slave trackers

Time	Power production of slave trackers (W)	Power production of master trackers (W)
11:00	14360	14407
11:10	14379	14455
11:20	14523	14617
11:30	12147	14697
11:40	12147	14766
11:50	12185	14792
12:00	12191	14815
12:10	12180	14809
12:20	12262	14875
12:30	12206	14817
12:40	12162	14758
12:50	12053	14666
13:00	12016	14644
13:10	12227	14826
13:20	12250	14840
13:30	12225	14886
13:40	12090	14799
13:50	15017	14922
14:00	14982	14813
14:10	15031	14831
14:20	14995	14902
14:30	14869	14915
14:40	15038	14932
14:50	14961	14818
15:00	15057	14892

Table 4 Shift angle of slave trackers

Time	Output Power without ancillary service (W)	Output power with active ancillary system service (W)	Angle Shift slave
9:00	72079	72079	0
9:10	72112	72112	0
9:20	74248	59398	16
9:30	74976	59981	16
9:40	75254	60203	16
9:50	76737	61390	16
10:00	76541	61233	16
10:10	78247	62598	16
10:20	78382	62706	16
10:30	77909	62327	16
10:40	78382	62706	16
10:50	80548	64438	16
11:00	79417	63534	16
11:10	79930	63944	16
11:20	79248	55474	28
11:30	80159	56111	28
11:40	78526	54968	28
11:50	79708	55796	28
12:00	79852	55896	28
12:10	79206	55444	28
12:20	78704	55093	28
12:30	79284	55499	28
12:40	79488	55642	28
12:50	79692	55784	28
13:00	80294	40147	47
13:10	80503	40252	47
13:20	79955	39978	47
13:30	77904	38952	47
13:40	79357	39679	47
13:50	78904	39452	47
14:00	79267	39634	47
14:10	79191	39596	47
14:20	79728	39864	47
14:30	78789	39395	47
14:40	78753	31501	64
14:50	77836	31134	64
15:00	78321	31328	64
15:10	78018	31207	64
15:20	77846	31138	64
15:30	76787	30715	64
15:40	76002	30401	64
15:50	74802	29921	64
16:00	74102	66692	7
16:10	71435	64292	7
16:20	69667	62700	7
16:30	68649	61784	7
16:40	62827	62827	0
16:50	57702	57702	0
17:00	49272	49272	0