

Methods for Integrating Solar Panels into The Power Grid Using Smart Grid Technologies

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Received: 29 August 2026; **Accepted:** 25 September 2026; **Published:** 23 October 2026

Abstract: The paper analyses methods for integrating solar photovoltaic plants into the power system using smart grid technologies. It is shown that the variable and only partially controllable nature of solar generation affects grid stability, voltage quality and power balance. Maximum power point tracking (MPPT) algorithms, smart inverters, advanced metering infrastructure (AMI), energy storage systems, microgrids, distributed energy resource management systems (DERMS) and demand response (DR) programmes are compared against a common set of criteria. The characteristics of a PV module and a daily load profile are illustrated by simulation. A concept for applying these methods jointly within a four-level hierarchical architecture is proposed, and practical recommendations for their implementation in Uzbekistan are given.

Keywords: Solar panel, smart grid, photovoltaic plant, smart inverter, MPPT, microgrid, energy storage, AMI, DERMS, renewable energy.

Introduction:

Solar Over the past decades, renewable energy sources, and solar photovoltaic (PV) systems in particular, have become one of the fastest-growing areas of the global energy sector. The sharp decline in PV module prices, tightening environmental requirements and the need to ensure energy security are driving the widespread adoption of solar power. However, connecting solar energy to the power grid on a large scale gives rise to a number of technical problems.

First, the output of PV plants changes sharply depending on solar irradiance, cloud cover and air temperature. Second, conventional distribution networks are designed for unidirectional power flow,

and the appearance of generation on the consumer side may lead to reverse power flows, voltages exceeding permissible limits and maloperation of protection devices. Third, inverter-interfaced sources reduce system inertia, which adversely affects frequency stability.

An effective way to solve these problems is to use intelligent power networks, i.e. smart grid technologies. A smart grid is an electric power system that coordinates the generation, transmission, distribution and consumption of electricity in real time by means of digital communications, sensors, automated control and information technologies [1, 2].

The basic principles of the smart grid concept are set out in the work of H. Farhangi [1], which presents the transition from the conventional grid to a smart grid as a step-by-step process, with advanced metering infrastructure as its foundation. X. Fang et al. [2] provided a comprehensive review of the smart grid from the standpoint of smart infrastructure, smart management and smart protection systems. With regard to improving the efficiency of PV systems, T. Esram and P. Chapman [3] presented the most complete comparative analysis of MPPT techniques. Converter technologies and control strategies for grid-connected PV systems have been studied in depth by S. Kouro et al. [4] and F. Blaabjerg et al. [9].

The microgrid concept was proposed by R. Lasseter [5]; later, D. Olivares et al. [6] systematised the hierarchical (primary, secondary and tertiary) structure of microgrid control. Requirements for interconnecting distributed resources with the grid are specified in IEEE 1547-2018 [7], and communication protocols in substations are defined in IEC 61850 [8]. Smart grid communication technologies were analysed by V. Gungor et al. [10].

The literature review shows that most existing studies are devoted to individual technologies, whereas considering them within a unified integration architecture, especially under the conditions of developing power systems, has not been sufficiently investigated.

The aim of the study is to systematise the main methods of integrating solar panels into the grid by means of smart grid systems, to compare their advantages and disadvantages against a common set of criteria, and to propose a hierarchical model for their joint application.

METHODS

The study employed methods of system analysis, comparative analysis, generalisation and computer simulation. On the basis of scientific literature, international standards and reports of international organisations [1–11], the integration methods were

assessed against the following criteria: impact on grid stability, energy efficiency, technical complexity, economic cost and interoperability with smart grid infrastructure.

The integration methods were grouped by functional level: device level (PV module and inverter), consumer level (household and enterprise), distribution network level and power system operator level.

The current–voltage (I–V) and power–voltage (P–V) characteristics of the PV module were calculated in Python on the basis of the single-diode equivalent circuit model. The following parameters were adopted: short-circuit current under standard test conditions $I_{sc} = 9.5$ A, open-circuit voltage $V_{oc} = 38$ V, number of series-connected cells $N_s = 60$, diode ideality factor $n = 1.3$, temperature $T = 25$ °C. The Volt–VAr and Volt–Watt characteristics of smart inverters were constructed using the default settings specified in IEEE 1547-2018 for Category B [7]. To evaluate the effect of the energy storage system, typical (illustrative) daily load and PV generation profiles expressed in per-unit values were used.

RESULTS

The analysis identified seven main methods of integrating solar panels via the smart grid. Their essence and impact on the grid are described below.

1. Maximum power point tracking (MPPT)

The I–V characteristic of a PV module is nonlinear, and for every value of irradiance and temperature there is a single maximum power point (MPP). MPPT algorithms control the operating mode of the converter so that the module always operates in the vicinity of this point. The simulation results (Fig. 1) show that when irradiance decreases from 1000 W/m² to 400 W/m², the power at the MPP falls from approximately 289 W to 109 W, i.e. almost in proportion to irradiance, whereas the MPP voltage varies within a relatively narrow range (30.6–32.3 V). It is precisely this property that underlies the voltage-based operation of MPPT algorithms.

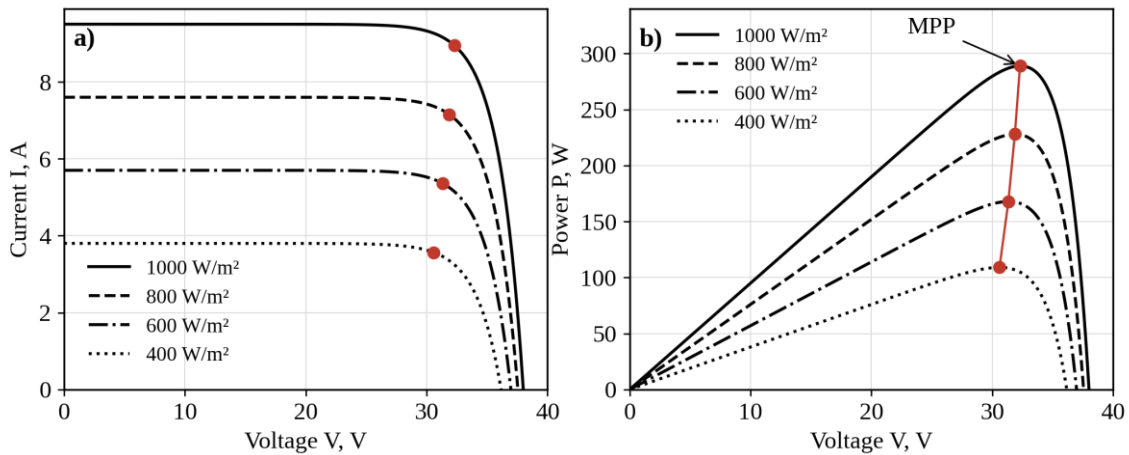


Fig. 1. I–V (a) and P–V (b) characteristics of the PV module at different irradiance levels ($T = 25\text{ }^{\circ}\text{C}$; MPP – maximum power point)

The most widely used methods are the Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms [3]. Because several local maxima appear on the P–V curve under partial shading, intelligent techniques such as artificial neural networks, fuzzy logic and particle swarm optimisation (PSO) are also applied.

In a smart grid environment, the MPPT function acquires a new significance: on a signal from the grid operator, the inverter may hold its output below the maximum power point (power reserve mode). This reserve is used for frequency regulation.

2. Smart inverters

Conventional inverters merely convert direct current into alternating current and disconnect when a grid fault occurs. Smart inverters, by contrast, provide active grid-support functions. According to IEEE 1547-2018 [7], these functions include:

- voltage–reactive power (Volt-VAR) control: absorbing reactive power when the voltage rises and

injecting it when the voltage drops;

- preventing the voltage from exceeding permissible limits by means of voltage–active power (Volt-Watt) control;
- frequency–active power (Frequency-Watt) response;
- continued operation without disconnection from the grid during short-term voltage and frequency deviations (ride-through);
- remote modification of settings via a communication interface.

The Volt-VAR and Volt-Watt characteristics are shown in Fig. 2. When the voltage is within 0.98–1.02 p.u., the inverter does not exchange reactive power (dead band). When the voltage reaches 1.08 p.u., the inverter absorbs reactive power of up to 44 % of its rated apparent power; above 1.06 p.u. it begins to curtail active power linearly, reducing it to 20 % of rated power at 1.10 p.u. [7].

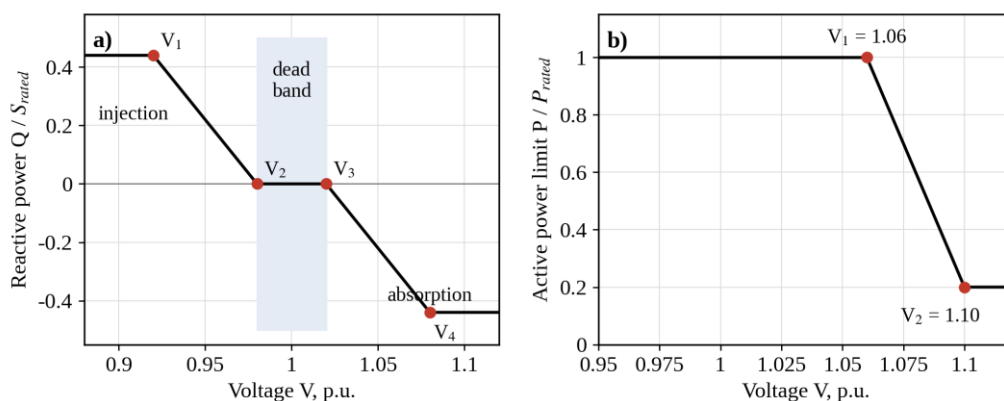


Fig. 2. Volt-VAR (a) and Volt-Watt (b) characteristics of a smart inverter (IEEE 1547-2018, Category B default settings)

In the future, grid-forming inverters will become increasingly important. By emulating the behaviour of a synchronous generator (virtual inertia), they ensure frequency stability in low-inertia systems.

3. Advanced metering infrastructure (AMI)

AMI consists of smart meters, communication networks and data management systems and provides two-way information exchange between the consumer and the grid operator [1]. In solar panel integration, AMI makes it possible to account separately for the energy exported to and imported from the grid (net metering or net billing), to monitor generation in real time, to detect faults and to apply dynamic tariffs. PLC, RF mesh, cellular (LTE, 5G) and fibre-optic networks are used as communication channels [10].

4. Energy storage systems

Battery energy storage systems (BESS) are among the

most effective means of compensating for the variability of solar generation. They store surplus energy during the day and return it to the grid during the evening peak, limit the rate of power change (ramp-rate control) and provide frequency regulation services. An energy management system (EMS) draws up an optimal charge–discharge schedule based on forecasts, tariffs and the battery state of charge. At present, lithium-ion batteries are the most widespread technology.

The effect of the BESS on the daily profile is shown in Fig. 3. During daytime hours with high PV generation, the net load becomes negative (down to approximately -0.45 p.u.), which indicates reverse power flow. The BESS stores the surplus energy, thereby eliminating the reverse flow, and returns it in the evening hours, reducing the net load peak in the example considered from 0.90 p.u. to 0.55 p.u., i.e. by approximately 39 %.

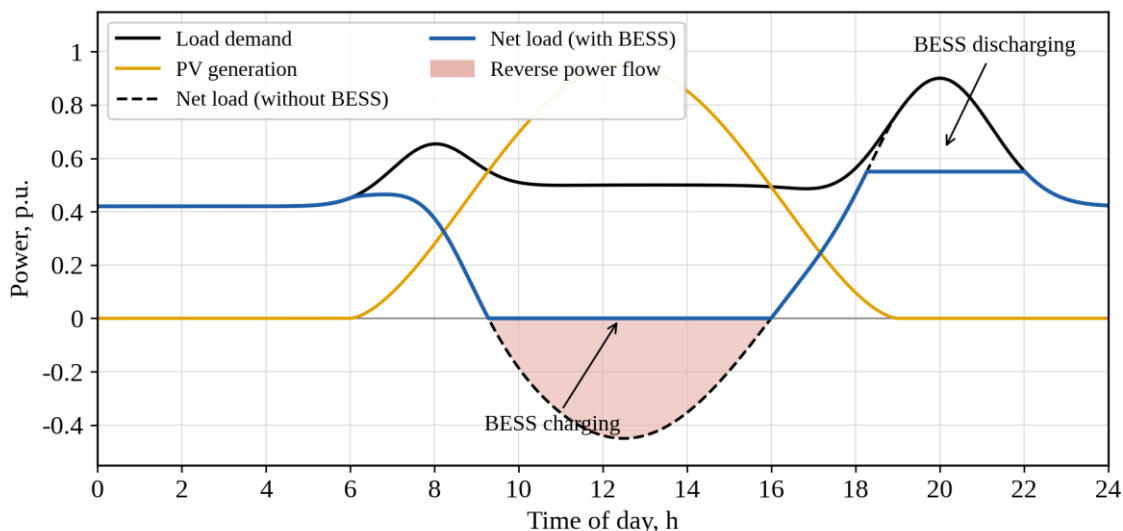


Fig. 3. Typical daily load, PV generation and net load (with BESS) profiles in a distribution network

5. Microgrids

A microgrid is a local system consisting of distributed sources, energy storage units and loads that, as a single controllable entity, can operate either in parallel with the main grid or independently of it (in islanded mode) [5]. Microgrid control is usually implemented on the basis of a three-level hierarchy [6]:

1. **primary level** – local voltage and frequency regulation by inverters (e.g., droop control);
2. **secondary level** – restoration of voltage and frequency deviations and power sharing among

sources;

3. **tertiary level** – economic optimisation and management of power exchange with the main grid.

Microgrids significantly increase the reliability of power supply to remote areas, industrial zones and critical facilities (hospitals, data centres).

6. DERMS and virtual power plants

Controlling a large number of small solar installations individually is extremely complex in practice. Distributed energy resource management systems (DERMS) combine them on a single platform and control them while taking network constraints into

account. A virtual power plant (VPP), in turn, aggregates geographically dispersed PV installations, batteries and controllable loads into a single participant in the electricity market. Device interoperability is ensured by protocols such as IEC 61850 [8], IEEE 2030.5 [12] and OpenADR.

7. Demand response and artificial intelligence-based forecasting

Demand response (DR) programmes use price or incentive signals to encourage consumers to shift their load to hours of high solar generation. For example, water heaters, air conditioners, pumps and electric vehicle charging can be moved to daytime.

This method increases system flexibility without additional equipment.

Accurate forecasting of solar generation is one of the key prerequisites for smart grid control. Short-term forecasts are produced with machine learning models (LSTM neural networks, gradient boosting) using meteorological data, satellite imagery and sky camera data. This considerably facilitates the scheduling of reserve capacity.

Comparative analysis of the methods

The results of the comparative analysis are summarised in Table 1.

Table 1. Comparative characteristics of methods for integrating solar panels via the smart grid

Integration method	Main function	Advantages	Limitations	Relation to smart grid
MPPT algorithms (P&O, INC, intelligent methods)	Extracting maximum power from the panels	Easy to implement, high efficiency	Oscillations under rapid irradiance changes	Local control at the inverter level
Smart inverters	Voltage and frequency support, reactive power	Improve grid stability	Compliance with standards required	IEEE 1547-2018, remote configuration
AMI and smart meters	Two-way metering and data transmission	Real-time monitoring, net metering	Cybersecurity risks	Consumer–operator communication
Energy storage systems (BESS)	Matching generation and consumption	Smooth variability, reduce peaks	High upfront costs	Optimal charge–discharge via EMS
Microgrids	Autonomous control of local sources	Reliability, islanded mode	Complex protection and control	Hierarchical control system
DERMS and VPP	Unified control of distributed sources	Scalability, market participation	Complex software	Optimisation at the operator level
DR and forecasting	Adapting consumption to generation	Low-cost source of flexibility	Depends on consumer engagement	Price signals, artificial intelligence

DISCUSSION

The results of the analysis show that no single method can, on its own, fully solve the problem of integrating a high share of solar energy. MPPT and smart inverters ensure efficiency and local stability at the device level, energy storage and DR programmes maintain the balance over time, and DERMS and VPPs provide coordination at the system level. Therefore, the four-level hierarchical integration architecture

shown in Fig. 4 is proposed:

- 1. Device level:** MPPT algorithms and grid-supporting smart inverters;
- 2. Consumer level:** smart meter, home or building energy management system, battery and controllable loads;
- 3. Distribution network level:** microgrid controllers and DERMS, control of voltage and power flows;

4. System operator level: generation forecasting, market participation via VPPs and dispatch control.

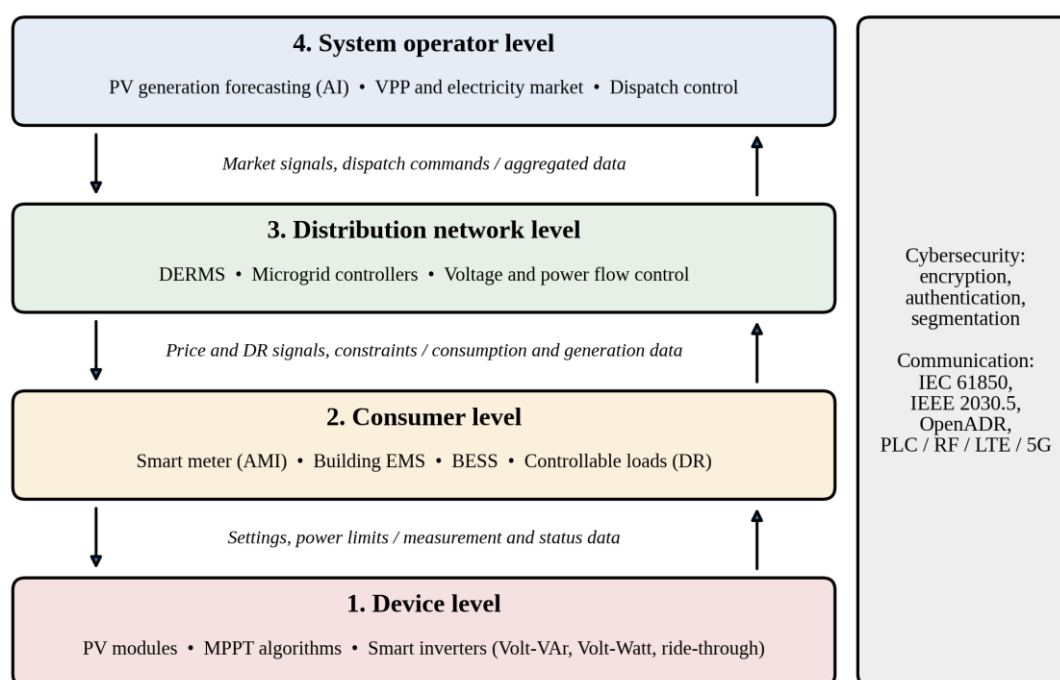


Fig. 4. Proposed four-level hierarchical architecture for integrating solar panels via the smart grid

In the proposed architecture, control signals (market and dispatch commands, price signals, power limits) are transmitted from the upper level downwards, while measurement and status data are transmitted from the bottom up. Information exchange between the levels should be based on standardised protocols. Cybersecurity requires particular attention here, since remote control of smart inverters and meters creates new attack vectors. Encryption, authentication and network segmentation measures must be an integral part of the architecture.

The results obtained are consistent with the conclusions reported in the literature: the hierarchical principle of microgrid control [6] and the layered structure of the smart grid [1, 2] form the theoretical basis of the proposed architecture. In this work, however, the hierarchy is extended beyond the microgrid to cover all levels from the device to the system operator, and specific integration methods are assigned to each level. A limitation of this approach is that it is currently conceptual, and quantitative performance indicators should be determined by simulation of a specific network.

Prospects for application in Uzbekistan

Owing to its large number of sunny days and high level of solar irradiance, Uzbekistan is one of the regions most favourable for solar power. The country has adopted the Law “On the Use of Renewable Energy Sources” [13], and the construction of large solar plants and the installation of rooftop solar panels on households are developing actively. This process necessitates the modernisation of distribution networks. On the basis of the analysis, the following practical recommendations have been developed:

- introducing IEEE 1547-2018 or equivalent national technical requirements for grid-connected inverters, in particular making Volt-VAr and ride-through functions mandatory;
- phased large-scale deployment of smart meters and their connection to a unified data platform;
- encouraging the installation of battery energy storage systems at large solar plants;
- implementing solar-plus-storage microgrids as pilot projects in remote and mountainous areas;
- developing solar generation forecasting models adapted to the climatic conditions of Uzbekistan

(dust, high summer temperatures);

- establishing cybersecurity requirements for the energy sector and training specialists.

CONCLUSION

Large-scale integration of solar panels into the power grid faces serious technical challenges within the conventional grid infrastructure. Smart grid technologies offer a comprehensive solution to these problems. In this study, MPPT algorithms, smart inverters, AMI, energy storage systems, microgrids, DERMS and DR programmes were systematised and comparatively analysed against a common set of criteria.

The simulation results showed that the power of a PV module varies almost in proportion to irradiance, that smart inverter functions make it possible to keep the voltage within permissible limits, and that an energy storage system eliminates reverse power flow and significantly reduces the evening peak load (by approximately 39 % in the example considered).

The main conclusion is that effective integration can be achieved only by applying these methods jointly within a unified hierarchical architecture, together with standardised communication protocols and reliable cybersecurity measures. The proposed four-level model can serve as a practical basis for modernising the power system of Uzbekistan and increasing the share of renewable energy. Future research will focus on a quantitative assessment of the proposed architecture by computer simulation of a specific distribution network.

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