WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Impact of Solar Power Generation on the Electrical Grid

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ABSTRACT—

The rapid growth of solar photovoltaic (PV) generation is changing how electrical grids are planned and operated, because PV is variable, inverter-interfaced and mostly connected at distribution level. This paper assesses the impact of solar power on the grid through three analytical models: net load and ramping, voltage rise on a radial feeder, and frequency response under reduced system inertia. A case study with a representative residential-dominated daily load profile and a weak feeder is used to quantify each effect. Reverse power flow appears at about 50 % PV penetration (installed PV as a share of feeder peak load); the maximum three-hour evening ramp of the net load grows from 0.56 to 0.72 pu of peak load as penetration rises from 0 to 80 %; and the midday voltage limit of 1.05 pu is reached at 91 % penetration with unity-power-factor inverters but at 109 % when inverters absorb reactive power at a power factor of 0.95. With 60 % of generation non-synchronous, the initial rate of change of frequency after a 5 % generation loss rises from 0.25 to 0.63 Hz/s. Mitigation measures are reviewed and a prioritised set of recommendations is given. The results are analytical and rely on representative assumptions; validation with measured feeder data is the next step.

***Index Terms*—Distributed generation, grid integration, hosting capacity, photovoltaic systems, power quality, system inertia, voltage regulation.**

I. INTRODUCTION

Solar photovoltaic (PV) capacity has grown rapidly in recent years, driven by falling module costs, supportive policies and the wish to decarbonise electricity supply. Unlike conventional power stations, much of this capacity is installed on rooftops, farms and small plants connected to low- and medium-voltage distribution feeders, which were designed for one-way power flow from the substation to consumers [1]. PV output follows irradiance, so it rises and falls with the sun and with passing cloud, and it is delivered to the grid through power-electronic inverters rather than rotating synchronous machines [2].

These characteristics create new technical questions. Midday generation can exceed local demand and push power back toward the substation, raising voltage along the feeder. The sharp fall of PV output in the evening, as demand is rising, produces steep ramps that conventional plants must follow; the resulting shape of net load is widely known as the "duck curve" [3]. As synchronous plants are displaced, the inertia that slows frequency deviations declines. Power quality, protection coordination and metering are affected as well.

The objectives of this paper are (i) to classify the principal impacts of solar PV on the grid; (ii) to formulate compact analytical models for net load, feeder voltage and frequency response; (iii) to quantify the impacts through a case study; and (iv) to summarise mitigation measures and give recommendations suitable for engineers and for diploma-level study. The study is analytical: input data are representative assumptions and not measurements, and the conclusions are stated accordingly.

Section II gives background, Section III classifies impacts, Section IV develops the models, Section V defines the case study, Section VI presents results, Section VII discusses mitigation, and Sections VIII and IX give limitations and conclusions.

II. BACKGROUND

A. PV Generation and the Inverter Interface

A PV array converts irradiance into direct current, and a grid-tied inverter converts it to alternating current at the grid frequency. The inverter tracks the maximum power point, so active power is determined by weather and not by system needs, unless it is deliberately curtailed. Inverters respond within milliseconds, have no rotating mass, and can control reactive power within their current rating, which makes them both a challenge for stability and a resource for voltage control [2]. Daily PV output is smooth on a clear day and highly variable on partly cloudy days; here a clear day is assumed so that the systematic effects can be isolated.

B. Grid Codes and Standards

Interconnection of distributed resources is governed by standards such as IEEE Std 1547-2018, which sets requirements for voltage regulation, ride-through and anti-islanding [4]. Supply voltage quality in public low-voltage networks is specified in EN 50160, which requires the 10-minute

mean r.m.s. voltage to stay within ±10 % of nominal for 95 % of a week [5]. Harmonic distortion at the point of common coupling is addressed in IEEE Std 519-2014 [6]. This paper uses 1.05 pu as an upper planning voltage limit for feeders, a design assumption that leaves margin below the statutory band.

C. Solar Resource and Variability

Clear-sky PV output follows the path of the sun: it is zero at night, rises after sunrise and peaks near solar noon, so that the daily generation profile is concentrated into a few hours that are only loosely related to the shape of demand. Passing cloud can reduce the output of a single plant by a large fraction within seconds to minutes, whereas the combined output of plants spread over a wide area is smoother because clouds rarely cover all sites at once. Output also varies with season, temperature and soiling. For these reasons, planning studies normally consider several operating points, such as a sunny day at light load, rather than a single average condition, and the clear-day profile used here represents the worst case for midday voltage rise.

III. IMPACTS OF SOLAR PV ON THE GRID

Table I summarises the main impacts. They differ in the part of the grid affected and in the time scale, from milliseconds for protection and frequency to the daily cycle for net load.

TABLE I

PRINCIPAL IMPACTS OF SOLAR PV ON THE GRID

Impact	Cause	Consequence
Voltage rise	Generation exceeds local demand on a weak feeder	Overvoltage, inverter trips, curtailment
Reverse power flow	Surplus PV exported to the substation	Loading of transformers; protection misoperation
Net-load ramps	Fall of PV output as evening demand rises	Fast ramping of conventional plants
Low inertia	Displacement of synchronous generation	Faster frequency change after disturbances
Power quality	Inverter harmonics; fast PV fluctuation	Voltage distortion and flicker
Protection	Bidirectional flow; limited inverter fault current	Blinding, false tripping, islanding

Voltage rise is usually the first limit met on distribution feeders, because the feeder resistance is significant and a few households can export together [7]. Reverse flow can overload equipment sized for demand in one direction and complicate directional and overcurrent protection. Net-load ramping is a system-level effect, since PV output falls rapidly around sunset just as residential demand peaks [3]. Reduced inertia makes frequency less stable, and inverter harmonics and rapid cloud-induced fluctuations can degrade power quality at the point of common coupling [6]. Because inverters supply only a limited fault current, protection settings based on conventional fault levels may need revision, and anti-islanding protection is required [4].

Not all effects are adverse. PV reduces daytime energy drawn from the bulk system, relieves loading of feeders and transformers at the time of generation, and, with suitable inverter control, can support voltage [8]. The aim of planning is to keep the benefits while staying within technical limits [10].

IV. ANALYTICAL MODELS

A. Net Load and Ramp

Let $P_{\mathrm{l}}(t)$ be the load and $P_{\mathrm{u}}(t)$ the PV output per unit of installed capacity. For a PV capacity p (in pu of peak load), the net load seen by the feeder or system is

$$P_{\mathrm{net}}(t) = P_{\mathrm{l}}(t) - p\,P_{\mathrm{u}}(t) \tag{1}$$

Reverse flow occurs when $P_{\mathrm{net}} < 0$. Two indicators are used: the maximum three-hour ramp, $\rho = \max\,[P_{\mathrm{net}}(t + 3\ \mathrm{h}) - P_{\mathrm{net}}(t)]$, and the daily reverse-flow energy,

$$E_{\mathrm{rev}} = \int \max[0, -P_{\mathrm{net}}(t)]\ \mathrm{d}t \tag{2}$$

B. Feeder Voltage

The feeder is represented by a series impedance $R + \mathrm{j}X$ between a source at voltage V_{s} and a point of common coupling (PCC) where load and PV are connected, as in Fig. 1. For a small voltage drop, the PCC voltage in per unit is approximately [11], [12]

$$V \approx V_{\mathrm{s}} + R(P_{\mathrm{pv}} - P_{\mathrm{l}}) + X(Q_{\mathrm{pv}} - Q_{\mathrm{l}}) \tag{3}$$

where P_{pv} and Q_{pv} are the PV active and reactive injections and P_{l}, Q_{l} the load. Equation (3) shows that net export raises the voltage, and that absorption of reactive power by the inverter ($Q_{\mathrm{pv}} < 0$) lowers it, which is the basis of volt-var control [8].

C. Hosting Capacity

The hosting capacity is the largest PV capacity that keeps V within the limit $V_{\max}$. Writing $P_{\mathrm{pv}} = p\,P_{\mathrm{u}}$ and $Q_{\mathrm{pv}} = q\,P_{\mathrm{pv}}$, solving (3) for p at the critical

midday hour gives

$$p_h = (V_{max} - V_s + R\,P_l + X\,Q_l) / [P_u\,(R + X\,q)] \quad (4)$$

For an inverter operating at power factor cos φ and absorbing reactive power, $q = -\tan(\arccos\cos\varphi)$, which equals −0.329 for cos $\varphi = 0.95$. A larger $|q|$ lowers the denominator of (4) and raises p_h, but requires an inverter rating above the active power, or a reduction of active power at the highest output.

D. Frequency Response

Immediately after a loss of generation ΔP (pu of system base), the rate of change of frequency (RoCoF) follows from the swing equation [13]:

$$\text{RoCoF} = \Delta P\,f_0 / (2\,H_{sys}), \quad H_{sys} = H_s\,(1 - s) \quad (5)$$

where f_0 is the nominal frequency, H_s is the inertia constant of the synchronous fleet and s is the instantaneous share of non-synchronous generation, assumed to displace synchronous machines and therefore to remove their inertia from the system.

V. CASE STUDY

A residential-dominated daily load profile is used, with a morning shoulder, low daytime demand and an evening peak at about 20:00, normalised to a peak of 1 pu; the noon load is 0.42 pu and the daily energy is 12.2 pu·h. PV output is that of a clear day, a half-sine-like curve between 06:00 and 18:00 reaching 0.85 pu of installed capacity at noon. The load and PV profiles are synthetic and chosen to be representative, not taken from measurements. Parameters are listed in Table II.

TABLE II

CASE-STUDY PARAMETERS

Parameter	Value
PV penetration p	0–140 % of feeder peak load
PV output at noon P_u	0.85 pu of installed capacity
Feeder R, X	0.08 pu, 0.04 pu (base: peak load)
Source voltage V_s	1.03 pu
Load power factor	0.90 lagging ($Q_l = 0.484\,P_l$)
Voltage limit V_{max}	1.05 pu (planning limit)
Inverter reactive power q	0 (unity); −0.329 (pf 0.95, absorbing)
H_s, ΔP, f_0	5 s, 0.05 pu, 50 Hz

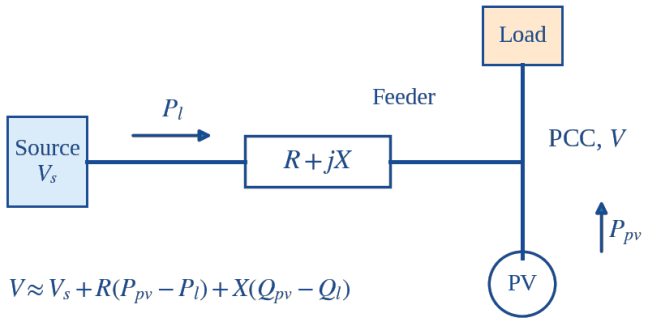


Fig. 1. Single-bus feeder model: a source feeds a load and a PV plant at the PCC through a series impedance.

The feeder impedance gives a voltage drop of about 0.10 pu at peak load, so the voltage at the PCC at 20:00 is 0.93 pu, inside the ±10 % band of [5]. The source voltage is set above nominal, as is common practice for feeders with a high evening drop, which reduces the headroom available for PV at midday.

VI. RESULTS AND DISCUSSION

A. Net Load

Fig. 2 shows the load and the net load for PV penetrations of 40 % and 80 %. The midday load is displaced by PV while the evening peak remains unchanged, so the net-load curve develops a deep midday valley and a steeper evening rise. Table III gives the indicators from (2). The daily minimum of net load, which is 0.36 pu without PV, reaches zero at about 50 % penetration and becomes negative above it, which marks the onset of reverse flow. At 80 % penetration, PV supplies 39 % of the daily energy but 0.99 pu·h of surplus is exported, and the maximum three-hour ramp is 0.72 pu, 29 % more than the 0.56 pu without PV.

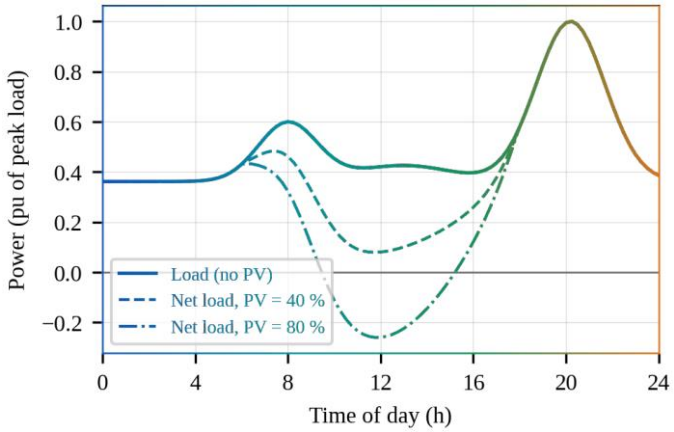


Fig. 2. Daily load and net load for PV penetrations of 40 % and 80 % of feeder peak load (clear day).

TABLE III

NET-LOAD INDICATORS VERSUS PV PENETRATION

p (%)	Min. net load (pu)	3-h ramp ρ (pu)	E_{rev} (pu·h)	PV energy share
0	0.36	0.56	0	0 %
20	0.25	0.59	0	10 %
40	0.08	0.63	0	20 %
60	−0.09	0.67	0.23	29 %
80	−0.26	0.72	0.99	39 %

B. Voltage Rise and Hosting Capacity

Fig. 3 plots the midday PCC voltage from (3) against penetration. With unity power factor, the voltage reaches the 1.05 pu limit at 91 % penetration, from (4); with inverters absorbing reactive power at a power factor of 0.95, the limit is reached at 109 %. Reactive power control therefore raises the hosting capacity by 18 percentage points, about 20 % in relative terms, without any loss of energy. Table IV lists the voltages. The benefit is limited because the feeder is resistive: the voltage rise is dominated by $R\,P_{pv}$, which reactive power can offset only in part.

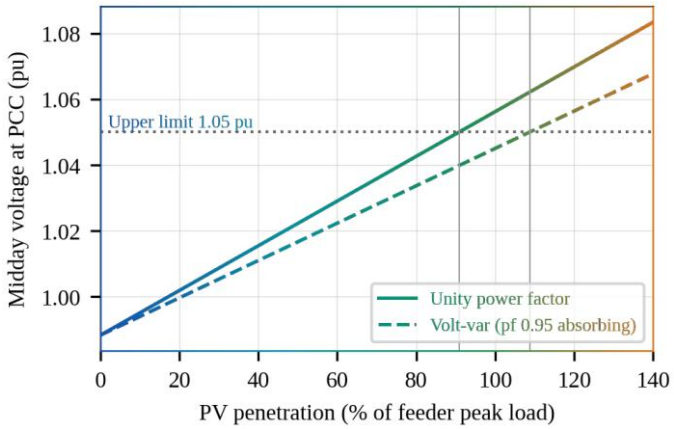


Fig. 3. Midday PCC voltage versus PV penetration with unity power factor and with volt-var control.

TABLE IV

MIDDAY PCC VOLTAGE (PU)

p (%)	Unity pf	Volt-var (pf 0.95)	Within 1.05 pu
0	0.988	0.988	Yes
40	1.015	1.011	Yes
80	1.043	1.034	Yes
100	1.056	1.045	Volt-var only
120	1.070	1.056	No

As a worked check at 80 % penetration with unity power factor, $P_{pv} = 0.85 \times 0.8 = 0.68$ pu, $P_l = 0.421$ pu and $Q_l = 0.204$ pu, so (3) gives $V = 1.03 + 0.08 \times (0.68 - 0.421) + 0.04 \times (0 - 0.204) = 1.043$ pu, as in Table IV.

C. Sensitivity of Hosting Capacity

Table V varies one parameter at a time using (4). The hosting capacity is most sensitive to the source voltage and to the feeder resistance. Lowering V_s from 1.03 to 1.00 pu raises the capacity from 91 % to 135 % with unity power factor, while raising it to 1.04 pu lowers it to 76 %. A feeder with a lower resistance (0.06 pu) hosts 105 % and gains more from volt-var control (134 %), because its reactance is relatively larger. A lighter midday load of 0.30 pu reduces the capacity to 73 %, which shows why the minimum daytime load, not the average, should be used in assessments. The tap setting has a limit, however: with $V_s = 1.00$ pu the evening voltage falls to 0.90 pu, the bottom of the ±10 % band, so the source voltage cannot be lowered further without reinforcing the feeder.

TABLE V

HOSTING CAPACITY (% OF PEAK LOAD) FROM (4)

Case	Unity pf	Volt-var (pf 0.95)
Base case	91	109
$R = 0.06$ pu	105	134
$R = 0.12$ pu	77	87
$V_s = 1.00$ pu	135	162
$V_s = 1.04$ pu	76	91
Midday load 0.30 pu	73	88
Midday load 0.60 pu	117	140

D. Reverse Flow and Ramping at Higher Penetration

Fig. 4 extends the analysis to 120 %. Reverse-flow energy grows faster than penetration once the valley passes zero; at 100 % it is 1.9 pu·h per day, which is 32 % of the PV energy generated on that feeder. The three-hour ramp also keeps rising, reaching 0.84 pu at 120 %. For a feeder with a peak of 1 MW, the surplus corresponds to about 1.9 MWh per day, an indication of the storage or flexible demand needed to absorb it, before conversion losses.

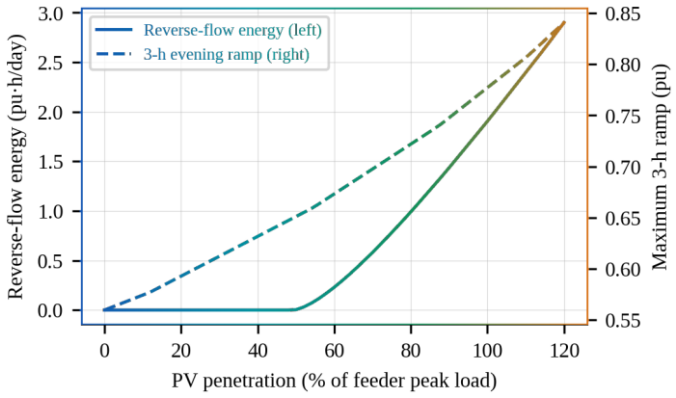


Fig. 4. Daily reverse-flow energy and maximum three-hour net-load ramp versus PV penetration.

E. Frequency Stability

Table VI gives RoCoF from (5). With no non-synchronous generation, a 5 % generation loss gives 0.25 Hz/s on a 50 Hz system. With 60 % non-synchronous share, effective inertia falls from 5 s to 2 s and RoCoF rises to 0.63 Hz/s, 2.5 times higher. Frequency relays and generator protection with fixed RoCoF settings may then operate for events that were previously ridden through, so inertia, fast frequency response or grid-forming inverters become important at high share.

TABLE VI

ROCOF VERSUS NON-SYNCHRONOUS SHARE

s (%)	H_{sys} (s)	RoCoF (Hz/s)	Ratio to s=0
0	5.0	0.25	1.0
20	4.0	0.31	1.25
40	3.0	0.42	1.7
60	2.0	0.63	2.5
80	1.0	1.25	5.0

F. Power Quality and Protection

Power quality and protection impacts cannot be reduced to one closed-form expression, but their direction follows from the same load flows. Inverters produce harmonic currents, and distortion at the point of common coupling must remain within the limits of [6]; fast PV fluctuations on a weak feeder cause voltage variations that may be perceived as flicker. Reverse flow changes the direction of fault current seen by feeder relays, and inverters limit fault current to a small multiple of rated current, which can reduce the sensitivity of overcurrent protection. Anti-islanding detection, as required by [4], is necessary because a feeder that is disconnected from the grid but fed by PV must not remain energised.

VII. MITIGATION AND RECOMMENDATIONS

A. Mitigation Measures

Table VII lists the main measures and what they address. The model suggests the following order of priority for a feeder that approaches its hosting capacity: first, enable inverter reactive-power control, which costs little and raised the hosting capacity here by 18 percentage points; second, allow limited active-power curtailment at the highest voltages, which removes the few hours that set the limit [9]; third, add storage or shift flexible demand into the midday valley, sized from the reverse-flow energy of Fig. 4; and fourth, reinforce the feeder or adjust transformer taps, which lowers R and directly reduces the voltage rise in (3).

TABLE VII

MITIGATION MEASURES

Measure	Addresses	Remark
Volt-var control	Voltage rise	Low cost; limited on resistive feeders [8]
Active power curtailment	Voltage, reverse flow	Loses energy; few hours per year [9]
Storage / flexible load	Ramp, reverse flow	Size from E_{rev}; add cost
Feeder reinforcement	Voltage, loading	Lowers R; capital intensive
Forecasting, scheduling	Ramps	Prepares conventional plant
Grid-forming inverters	Low inertia	Provide synthetic inertia

At system level, forecasting of PV output and scheduling of flexible plant prepare the grid for the evening ramp, and time-of-use tariffs encourage consumption during the solar peak. To address inertia, inverters with grid-forming or fast frequency response functions, together with synchronous condensers where appropriate, can be specified, and protection settings should be reviewed as the share of inverter-based generation grows. Technical limits should be agreed in advance with the network operator, based on the standards in Section II-B.

B. Operational Considerations

Distribution utilities often have limited visibility of rooftop PV. Where customers are billed on net energy, a meter records only the difference between consumption and generation, which hides the gross output that determines the voltage and reverse-flow behaviour analysed here. Monitoring at the head of the feeder and at selected customer points allows reverse flow and voltage excursions to be observed and the models in this paper to be calibrated. Operators also need clear connection procedures that state the study required, the inverter settings to be applied and the actions to be taken when a feeder reaches its hosting capacity, so that new connections are handled consistently and transparently.

C. Recommendations

1) Assess the hosting capacity of each feeder using measured minimum daytime load and irradiance data before approving new PV connections.
2) Require inverters to provide volt-var and related voltage-support functions in line with [4], with documented default settings.
3) Set transformer tap and feeder voltage targets with both the midday maximum and the evening minimum in view.
4) Install monitoring at feeder heads to measure reverse flow, voltage and gross PV output.
5) Plan storage, controllable loads and time-of-use tariffs in proportion to the surplus energy and ramps in Fig. 4.
6) Review protection and anti-islanding settings as PV penetration grows, and specify frequency-support capability for new inverters.

VIII. LIMITATIONS AND FUTURE WORK

The study is analytical and idealised. A single-bus feeder with lumped load and PV replaces a real network with distributed loads, tap changers and unbalance; the approximate voltage expression (3) neglects higher-order terms; a clear-day PV profile ignores cloud variability; the load profile is synthetic; and the inertia model assumes that non-synchronous generation displaces synchronous machines in proportion. The parameter values are assumed. Future work should (i) validate the results with measured feeder and irradiance data, (ii) use a multi-bus unbalanced load-flow model, (iii) include storage and tap control in the simulation, and (iv) study harmonics and fault current using detailed inverter models.

IX. CONCLUSION

Analytical models of net load, feeder voltage and frequency response were used to quantify the impact of solar PV on the grid. In the case study, reverse flow appears at about 50 % penetration, the evening ramp grows by 29 % at 80 %, the midday voltage limit sets the hosting capacity at 91 %

with unity power factor and 109 % with volt-var control, and a 60 % non-synchronous share raises RoCoF to 2.5 times its initial value. The impacts are manageable when they are anticipated: reactive-power control, limited curtailment, storage and flexible demand, feeder reinforcement and inverter-based frequency support together allow high PV penetration. The findings are indicative and should be confirmed by measurements and detailed network studies.

ACKNOWLEDGMENT

The author thanks [Guide Name] and [Name of Institute] for guidance and facilities.

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