Review Article

Dynamic and Power-Quality Impacts of High Photovoltaic Penetration on Distribution Feeders That Static Load-Flow Studies Overlook

Utku Tanrısever[1], Mehmet Bulut[1]

1. Department of Electrical and Electronics Engineering, University of Turkish Aeronautical Association (THK University), Turkey

Distributed photovoltaic (PV) generation on low- and medium-voltage distribution feeders has grown very quickly, and most studies of its impact use steady-state load-flow analysis. These studies do capture overvoltage and the distortion of the voltage profile under peak generation, but they leave out two effects that matter for how much PV a feeder can really host: the fast voltage changes caused by clouds passing over the panels, and the harmonic distortion that the inverters inject. This article reviews the published work on these two areas. It first sets out the basic equation for voltage rise on a feeder and uses it to explain why the high R/X ratio of distribution lines makes the voltage depend mainly on active power. It then looks at the dynamic side, where passing clouds cause fast power ramps that lead to voltage fluctuation, flicker, and extra switching of tap-changers and capacitor banks, none of which a single snapshot load-flow can show. It then checks inverter harmonic emission against the IEEE 519 limit of 5% total harmonic distortion at the point of common coupling and reviews the main filtering options. Finally it covers inverter-based mitigation under IEEE 1547-2018, in particular the volt-var and volt-watt functions. The main conclusion is that the limit on PV hosting capacity is often a dynamic or power-quality limit rather than a steady-state voltage limit, so assessing a feeder properly needs time-series and harmonic analysis on top of the usual load flow.

Corresponding author: Mehmet Bulut, mbulut@thk.edu.tr

 doi.org/10.32388/UHXYG9

1. Introduction

Electric distribution systems were historically designed as passive radial networks in which power flowed in a single direction, from the substation to the loads. Voltage along a feeder fell monotonically with distance, and regulation was managed with relatively slow devices: on-load tap-changing (OLTC) transformers, line voltage regulators, and switched capacitor banks. The widespread deployment of rooftop and distributed photovoltaic (PV) generation has overturned this assumption. When local PV output exceeds local demand, surplus power flows back toward the substation, and the feeder becomes an active, bidirectional network whose voltage can rise above nominal at the points of generation.

This shift has motivated a large volume of analysis, including many recent studies, that quantifies the impact of PV on feeder voltage using steady-state load-flow (power-flow) analysis. Such studies typically place PV at one or more buses, increase the penetration level, and report the resulting voltage profile at a single operating snapshot—usually peak generation against minimum load. This approach is valuable and correctly identifies steady-state overvoltage as a first-order concern. However, it captures only part of the problem.

1.1. Objectives and Scope

The purpose of this article is to review, organize, and analyze the published literature on two categories of PV impact that steady-state load-flow studies do not represent, and which are repeatedly identified in the literature as the principal limitations of "impact analysis" work:

- Dynamic (time-varying) voltage behaviour caused by the intermittency of solar irradiance, in particular the rapid power ramps produced by passing clouds, and the resulting voltage fluctuation, flicker, and stress on voltage-regulating equipment.
- Power-quality degradation, specifically the harmonic distortion injected by grid-connected PV inverters, its evaluation against the IEEE 519 standard, and the filtering techniques available to mitigate it.

The article also reviews inverter-based mitigation under IEEE 1547-2018, since the same power-electronic interface responsible for some impacts is also the primary tool for managing them. The scope is deliberately analytical and literature-based: the article does not present an original simulation, but rather presents the governing analytical relationships and synthesizes quantitative findings reported by others

on standard test systems such as the IEEE 13-, 33-, and 34-node feeders, and on real low-voltage networks.

1.2. Problem Statement

A steady-state load-flow gives the feeder voltage for one fixed set of injections. It therefore cannot represent how quickly voltage changes when a cloud reduces a PV plant's output by 70–80% within seconds, how many additional tap-change or capacitor-switching operations this variability forces over a day, or the harmonic spectrum that the inverter injects regardless of the steady-state power balance. As a result, a feeder that appears acceptable in a snapshot load-flow may, in operation, suffer flicker complaints, accelerated equipment wear, relay misoperation, and waveform distortion that exceeds standard limits. The core question of this article is therefore: what do these neglected dynamic and power-quality effects consist of, how can they be characterized analytically, and how do they reshape the assessment of PV hosting capacity?

2. Literature Review

Research on PV integration into distribution networks can roughly be split into three groups, and together they point to where this article fits in.

2.1. Steady-State Voltage and Hosting-Capacity Studies

The largest and easiest-to-find group of studies looks at steady-state voltage rise and hosting capacity. Index-based assessments on the modified IEEE 13-node feeder over a 24-hour window have linked reverse power flow directly to voltage rise along the feeder, confirming that the voltage slope reverses once the feeder starts exporting power [1]. Older utility-oriented work reached the same basic result: since voltage drop is what drives the power flow, reversing the power flow reverses the voltage gradient, so the PV buses end up being the high-voltage points on the feeder [2]. This reversal is shown in Figure 1, and its effect on the voltage profile along the feeder is shown in Figure 2. These are the kind of studies that most "impact on voltage profile" analyses are based on.

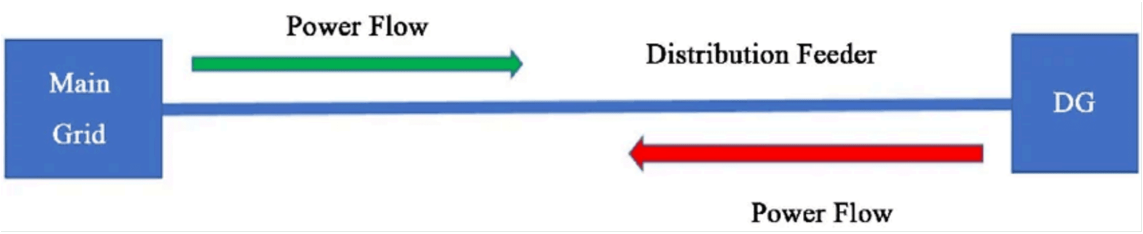


Figure 1. Power-flow direction on a distribution feeder: normal flow from the grid to the load, and reverse flow when distributed generation (DG) such as PV exports surplus power [3].

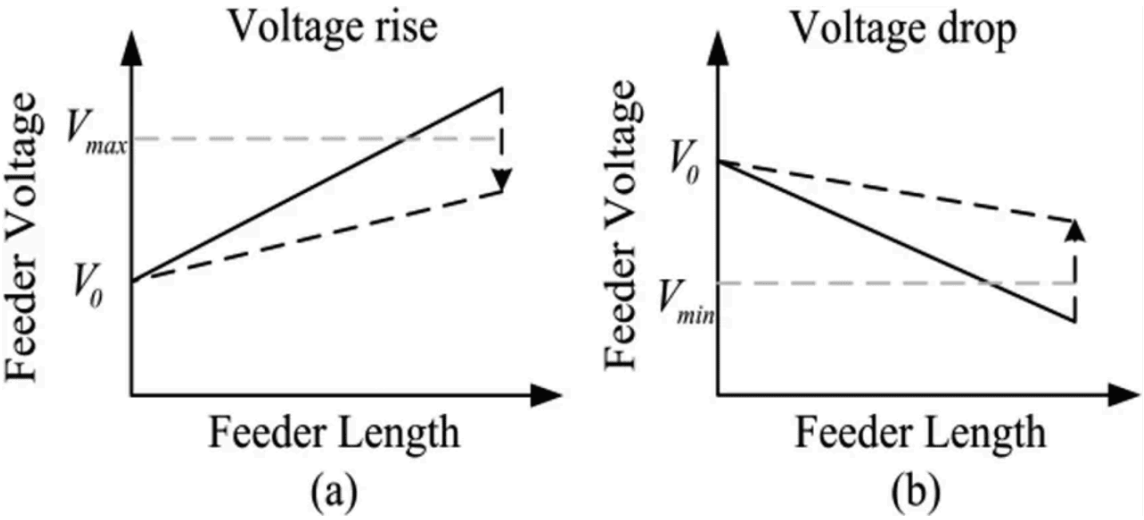


Figure 2. Voltage along a radial feeder: (a) voltage rise toward the feeder end under high PV/DG injection, and (b) the conventional voltage drop with load only [4].

2.2. Dynamic and Variability Studies

A second group of studies deals with the time-varying behaviour that the first group leaves out. Simulations that feed a distribution solver such as OpenDSS with cloud-shadow models have shown that when fast-moving clouds shade a cluster of PV systems, the combined output can drop to around 30% of full-sun levels, causing voltage sags, while clearing clouds cause overvoltage [5]. Measurement- and simulation-based work on low-voltage grids has found that problematic voltage fluctuations can show up at PV penetration as low as 40% of local rooftop capacity [6]. It is worth contrasting the two groups directly here: whereas Zeraati et al. [1] concentrate on voltage rise under steady-state conditions, Verbruggen et al. [6] show that the fluctuation itself can become the limiting factor even while the average

doi.org/10.32388/UHXYG9

voltage stays within limits. In other words, this group of studies keeps finding that it is the variability of PV output, not just its magnitude, that wears on the voltage-regulating equipment.

2.3. Power-Quality and Harmonic Studies

A third group of studies looks at harmonic emission from inverters. Since PV inverters build their AC output by switching at high frequency, they inject current harmonics, and the total of these is measured by the total harmonic distortion (THD). The literature consistently points to IEEE 519 [7] as the relevant standard, with the widely quoted 5% current-distortion limit at the point of common coupling, and discusses passive, active, and multi-level-topology approaches for staying under that limit.

2.4. Identified Gap

Looking across reviews of "impact analysis" work, two limitations keep coming up: there is usually no dynamic (transient) modelling and no varied weather scenarios such as cloudy or sudden-shading conditions, and the harmonic analysis and discussion of filtering solutions tend to be shallow. Because the same criticisms show up for several separate rooftop-PV voltage-profile studies, they seem to come from the steady-state-only method itself rather than from any one project doing a bad job. This is the gap this article tries to fill: instead of doing yet another steady-state voltage-profile assessment, it pulls together the dynamic and power-quality analysis that those assessments would need in order to be complete.

2.5. Comparative Analysis of Selected Studies

To turn this article into more of a review, three further studies were looked at in detail and compared against each other and against the main argument of this article. The three were chosen because they each approach high-PV distribution networks from a slightly different angle—one focuses on how PV is sized and placed, one is itself a broad review of hosting capacity, and one is a measurement-based case study of a fast PV disturbance—but all three end up touching the same core issues of voltage rise, time resolution, and power quality. The studies are Alrushoud and Lu [8], the hosting-capacity review by Qamar et al. [9], and the solar-eclipse case study by Sundararajan et al. [10].

Systems and methods used. The three studies are quite different in how they were actually carried out, which is useful because it means agreement between them is more convincing. Alrushoud and Lu [8] used simulation only, running OpenDSS together with MATLAB on the IEEE 123-bus feeder and on a real 6.1

MW feeder in North Carolina; their method was stochastic, placing PV randomly across many scenarios and sweeping the penetration from 5% up to 100% while recording the worst voltage each time. Qamar et al. [9] did not run a single network at all—theirs is a review paper that collects results from a large number of other studies, so its method is really the comparison itself. Sundararajan et al. [10] sat in between, using real measured 1-minute data from two actual PV systems (1.4 MW and 355 kW) during the 2017 solar eclipse and also building an OpenDSS model of the IEEE 8500-node feeder to see the effect on the voltage-regulating equipment. One point worth noting is that all three either use or quote the same voltage-rise relationship this article is built on: Sundararajan et al. write it as $\Delta V = [R(P_L - P_PV) + X(Q_L - Q_PV)] / V_base$, and Qamar et al. quote it as $\Delta V \approx (P{\cdot}R + Q{\cdot}X)/|V_n|$, which are the same equation used in Section 3, just written slightly differently.

Findings on voltage rise and hosting limits. All three agree that voltage rise from reverse power flow is the main thing that limits how much PV a feeder can take, but they put numbers on it in different ways. Alrushoud and Lu [8] found that the limit depends heavily on how the PV is modelled: with realistic (optimal-capacity) sizing the real feeder hosted PV all the way to 100% penetration (6.1 MW) with no violation, but with random or fixed-size allocation the same feeder went over the voltage limit, and the minimum hosting capacity fell from 2.04 MW to 1.6 MW just by changing the allocation method. Qamar et al. [9], pulling from many studies, give a similar but broader picture: one cited study was fine at 30% penetration but went outside limits at 50%, with several others reporting limits in the 30-50% range before mitigation. Sundararajan et al. [10] did not push their feeder to its limit, since they studied an eclipse at the existing ~37% penetration, but they confirmed the location effect—the PV system far from the substation caused a clear voltage rise at its connection point, while the one close to the substation barely moved the voltage. So the limit is real and is usually voltage, but the exact number depends on the feeder, the PV placement, and how the study is set up, which is itself one of the main points Qamar et al. make.

Findings on dynamics and power quality. This is the part most relevant to this article's argument. Alrushoud and Lu [8] do not study harmonics or transients directly, but they found that using 1-minute data instead of 30-minute data changed the hosting capacity a lot (2.04 MW dropping to 1.2 MW), because voltage regulators move the voltage over short time spans and fast data is needed to catch it—the same point this article makes about snapshots missing fast behaviour, reached from a data-resolution angle. Qamar et al. [9] back this up more directly, listing flicker and harmonics as their own separate limiting constraints: they report that flicker studies need seconds-to-minutes resolution, and that harmonics can

cut hosting capacity dramatically—in one cited case from about 90% down to 20% as nonlinear load increased, recovered to around 55% with a passive filter. Sundararajan et al. [10] give the actual measured numbers: during the eclipse, PV output dropped 70.8% and 84% on the two systems, voltage THD stayed safe at 3.4–4% (under the 5% IEEE 519 limit) but current THD was very volatile, swinging from 2% up to 35% because current THD rises as the fundamental current drops—exactly the mechanism described in Section 6. They also measured equipment wear, with one voltage regulator tapping 7 times on one phase and 5 on another during the event, and noted that although flicker stayed within limits (P_st around 0.09) this was at moderate penetration and could be worse higher up.

Aspect	Alrushoud & Lu [8]	Qamar et al. [9]	Sundararajan et al. [10]
Type of study	Simulation (OpenDSS + MATLAB)	Literature review	Measurement + simulation (OpenDSS)
System(s)	IEEE 123-bus + real 6.1 MW NC feeder	Many feeders from other papers	2 real PV systems + IEEE 8500-node feeder
Penetration studied	5%–100%	Varies (e.g. 30%, 50% cited)	~37% (existing)
Main limiting factor	Overvoltage only	Mostly voltage; also harmonics, flicker	Power quality during fast ramp
Voltage result	100% OK with optimal sizing; violates if random	OK at 30%, violates at 50% (one case)	Rise at far PV, little at near PV
Dynamic / PQ result	Not direct; 1-min vs 30-min data changes result	Harmonics cut HC 90%→20%; flicker needs fast data	Current THD 2–35%; voltage THD 3.4–4%; regulator tapped 7×/5×
Uses $\Delta V \approx (PR+QX)/V$?	Implicitly (overvoltage)	Yes, explicitly	Yes, explicitly

Table 1. Side-by-side comparison of the three reviewed studies.

Putting the three together, a few things stand out. First, all of them treat voltage rise from reverse power

flow as the starting problem, and two of the three use the exact voltage equation this article is built around, which gives some confidence that the analytical basis here is sound. Second, none of the three claims that steady-state voltage is the whole story: Alrushoud and Lu [8] show that time resolution changes the answer, Qamar et al. [9] list harmonics and flicker as separate limits, and Sundararajan et al. [10] measure the power-quality and equipment effects directly. That is basically the central argument of this article, reached by three different routes. Third, the studies disagree on the actual numbers (hosting limits anywhere from 30% to 100% depending on the case), which is not really a contradiction but a sign that these limits are very feeder-specific, as Qamar et al. point out explicitly. The main gap that still shows up, even across these three, is that detailed dynamic and harmonic analysis are usually done separately and at moderate penetration; Sundararajan et al. come closest to doing both at once with real data, but even they note their results are for ~37% penetration and could be more severe higher up. This supports the recommendation in this article that steady-state, time-series, and harmonic analysis should be combined rather than done in isolation.

3. Methodology

This article is a structured literature review and analytical synthesis. The methodology consists of three stages, described below, and is intentionally non-simulation-based; where quantitative values appear, they are drawn from the cited literature rather than from an original model.

3.1. Source Selection and Analysis Framework

Sources were selected to cover the three groups identified in Section 2, with priority given to peer-reviewed journal and conference papers, recognized standards (IEEE 519, IEEE 1547-2018), and national-laboratory technical reports. Each source was analyzed for (i) the phenomenon characterized, (ii) the analytical relationship or metric used, and (iii) the quantitative result reported, so that findings could be compared across different feeders and penetration definitions.

3.2. Analytical Relationships Used

Three standard relationships from distribution-system theory provide the analytical backbone of this article. The first is the two-bus voltage-rise approximation, which relates the voltage change across a line section to the injected active and reactive power and the line impedance. For a feeder section of

resistance R and reactance X carrying injected active power P and reactive power Q, the approximate voltage rise at the receiving end relative to the sending end is given in Equation (1):

$$\Delta V \approx (P \cdot R + Q \cdot X)/V \tag{1}$$

where V is the nominal voltage. In transmission systems X ≫ R, so voltage is controlled chiefly through reactive power Q. In distribution systems the resistance cannot be neglected; low-voltage cables exhibit R/X ratios of the order of four, so the P·R term dominates and feeder voltage becomes directly and strongly dependent on the active power injected by PV. This single relationship explains why distributed PV raises voltage so effectively, and why active-power curtailment is an effective (if wasteful) control lever in LV networks.

The second relationship is the power ramp rate, RR = ΔP/Δt, used to quantify the speed of PV output change during cloud transitions. The third is the definition of total harmonic distortion, the ratio of the root-sum-square of the harmonic components to the fundamental, used to evaluate inverter emission against IEEE 519. These are introduced in detail in Sections 5 and 6 respectively.

Worked example. To show how the voltage-rise relationship behaves on a real feeder, consider one phase of a 4.16 kV section of the IEEE 13-node feeder (line-to-neutral voltage V = 2402 V). Taking a representative section impedance of R = 0.45 Ω and X = 0.55 Ω, and a PV system exporting 500 kW at close to unity power factor (so P = 167 kW per phase and Q ≈ 0), the approximate voltage rise is ΔV ≈ (P·R + Q·X)/V = (167000 × 0.45)/2402 ≈ 31 V, or about 1.3% of nominal. If the inverter instead absorbs reactive power through its volt-var function—say 150 kvar (50 kvar per phase)—the rise falls to ΔV ≈ (167000 × 0.45 − 50000 × 0.55)/2402 ≈ 20 V, or about 0.82%. The example illustrates two of this article's points at once: that the active-power term sets most of the voltage rise, and that reactive control helps only partially because the resistive term still dominates.

3.3. Reference Systems

To keep the synthesis concrete, results are referred to standard test feeders where the cited literature uses them—principally the IEEE 13-node and 33-node systems for balanced and reconfiguration studies, and representative urban low-voltage residential feeders for variability studies. These systems are described in Section 4.

4. Reference Systems and Modelling Assumptions

Because this article synthesizes results across multiple studies, it is useful to characterize the systems on which those results were obtained, and the modelling assumptions that condition them.

4.1. Test Feeders

The IEEE 13-node feeder is a short, heavily loaded, unbalanced medium-voltage circuit widely used as a benchmark; index-based voltage-rise studies have used a balanced three-phase variant of it as a deliberately “weak” network in which PV impacts are pronounced. The IEEE 33-node system is a larger radial network commonly used for reconfiguration and loss studies. Low-voltage variability studies typically use real or representative urban residential feeders, where the high R/X ratio and the clustering of rooftop PV maximize voltage sensitivity. Figure 3 shows the standard IEEE 13-node feeder used as the main reference network in this article.

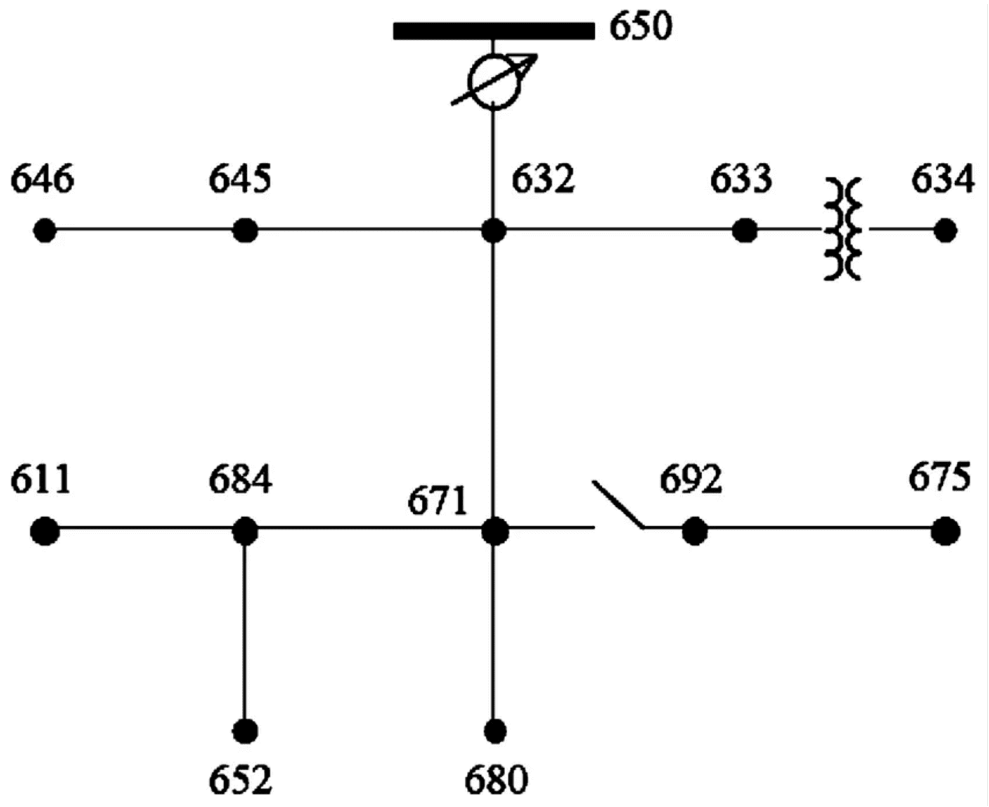


Figure 3. Single-line diagram of the IEEE 13-node distribution test feeder [11].

doi.org/10.32388/UHXYG9

4.2. Penetration Definition

A recurring source of confusion in PV-impact work is the definition of "penetration." It may be expressed relative to peak load, relative to installed transformer capacity, or relative to local rooftop capacity. The worst-case for voltage rise is high generation coincident with low load; some studies simplify by assuming zero feeder load during peak generation, in which case a stated penetration translates directly into net export. Comparisons across studies must account for these differing definitions, and this article notes the basis used wherever a numerical penetration value is quoted.

4.3. Representative Load and Generation Profiles

The dynamic effects that are the focus of this article only emerge under time-varying profiles. Two profile pairs are central. On the generation side, a clear-sky day produces a smooth diurnal PV curve, whereas a partly cloudy day superimposes deep, rapid excursions on that curve; it is the cloudy profile, not the clear-sky one, that drives the dynamic phenomena. On the load side, a residential feeder exhibits a midday demand trough that coincides with peak PV generation, maximizing reverse power flow, in contrast to a commercial feeder whose daytime load partially absorbs local generation. Table 2 summarizes these scenario pairings.

Profile dimension	Benign case	Stressing case
Irradiance	Clear sky (smooth curve)	Partly cloudy (rapid deep ramps)
Load coincidence	Commercial (daytime load absorbs PV)	Residential (midday trough, max export)
Analysis needed	Steady-state load-flow may suffice	Time-series + harmonic analysis required

Table 2. Profile pairings and the analysis each demands.

5. Dynamic Impacts of Cloud-Induced Variability

This section addresses the first gap: the short-timescale behaviour that steady-state load-flow cannot represent. The defining feature of PV as a distribution-connected source is that its output is set by an external, fast-varying driver—solar irradiance—rather than by dispatch.

5.1. The Physical Mechanism: Power Ramps

While the diurnal sun path causes slow, predictable output variation over hours, passing clouds cause rapid fluctuations on a timescale of seconds. The severity of a ramp is quantified by the ramp rate, RR = $\Delta P/\Delta t$. When a fast-moving cloud shades a geographically concentrated cluster of PV systems, aggregate output can drop to roughly 30% of full-sun output, and recover just as quickly when the cloud passes. Figure 4 shows this effect in a measured output trace, where the otherwise smooth daily curve is interrupted by sharp dips whenever clouds pass. At low penetration, such fluctuations are absorbed by the grid as negligible frequency deviations; at high penetration, the literature reports that they can challenge transient stability, cause voltage flicker, and in extreme cases threaten reliability.

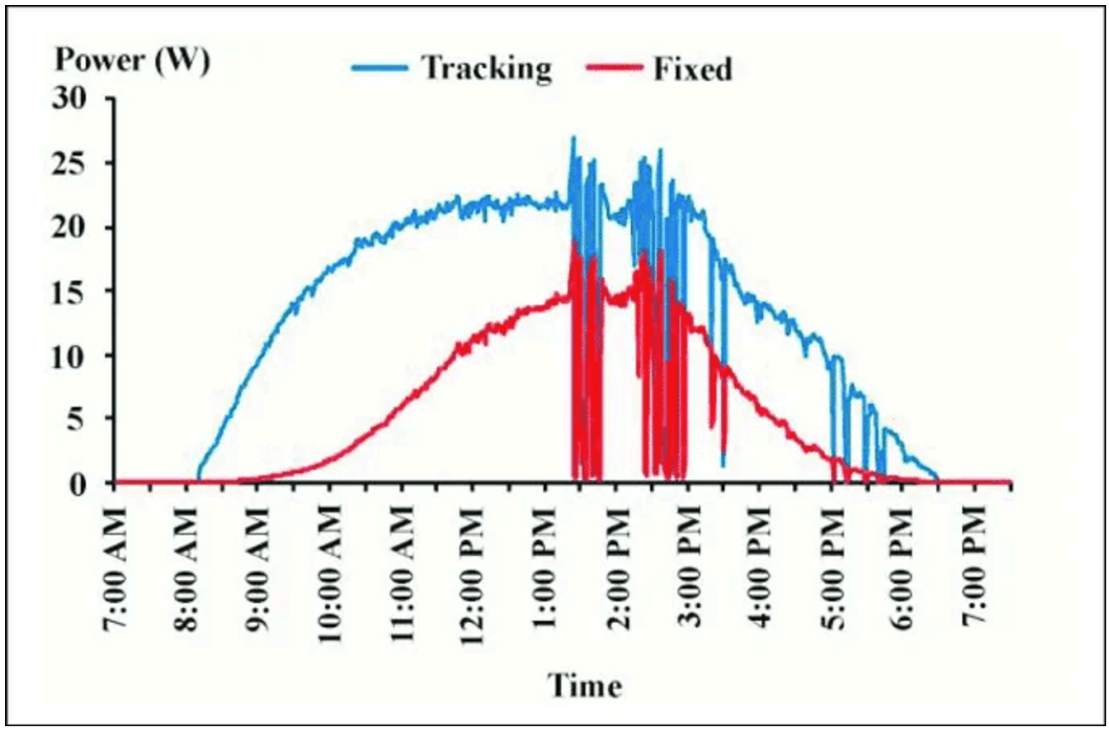


Figure 4. Measured PV output over a day. The sharp downward spikes in the early afternoon show the rapid, cloud-induced power fluctuations that are the focus of this section [12].

Geographic smoothing matters here. A spatially dispersed PV fleet experiences partial cancellation of individual ramps, but a tightly clustered subdivision—the typical rooftop-PV scenario—offers little smoothing and therefore represents the worst case for variability. This is precisely the configuration that steady-state studies model, yet they capture only its average, not its dynamics.

5.2. Voltage Fluctuation and Flicker

Applying the voltage-rise relationship of Section 3.2 dynamically, a rapid change ΔP in injected active power produces a near-proportional rapid change in feeder voltage, because of the dominant P·R term in LV networks. Repeated cloud-driven excursions therefore translate into repeated voltage excursions. When these occur in the frequency band to which the human eye is sensitive through lighting, they manifest as flicker. Studies of urban LV grids have found that problematic voltage fluctuations can begin at penetration levels around 40% of local rooftop capacity, and that the fraction of time during which fluctuations are problematic grows with penetration. A single snapshot load-flow, by construction, reports none of this.

5.3. Stress on Voltage-Regulating Equipment

Conventional regulation devices—OLTC transformers, line regulators, and switched capacitors—are electromechanical and slow, with deliberate time delays to avoid hunting. They were designed for the slow load cycle, not for second-scale generation swings. The literature consistently reports that cloud-induced variability forces these devices to operate far more frequently than under load-only conditions; one study of 20% PV penetration found that the tap-changer operated excessively even with a five-minute time delay. Each operation consumes mechanical life, so the hidden cost of variability is accelerated wear and increased maintenance of regulation assets. This is a capital-cost consequence that a voltage-profile snapshot cannot reveal.

5.4. Why Steady-State Analysis Misses This

What all of these effects have in common is that they depend on how fast the PV output is changing, not on its value at any single instant. A load-flow solves the network for one instant, so it has no way of seeing ΔP/Δt at all. To capture the dynamic impacts you need at least a quasi-static time-series simulation at sub-minute resolution, driven by a realistic cloudy-day irradiance profile, and for the very fastest effects a full dynamic (transient) simulation. The fact that this kind of analysis is usually missing is the most common criticism made of PV-impact studies.

6. Harmonic Distortion and Power Quality

This section addresses the second gap: the waveform distortion injected by inverters, which is independent of the steady-state power balance and is therefore not represented by fundamental-

frequency load-flow at all.

6.1. Origin of Harmonics in PV Inverters

A PV inverter converts DC to AC by switching power-electronic devices at high frequency, typically using pulse-width modulation (PWM). This switching synthesizes a fundamental-frequency sinusoid but also injects components at integer multiples of the fundamental—harmonics. The collective effect is measured by the total harmonic distortion. For current, THD is defined in Equation (2) as the ratio of the root-sum-square of the harmonic current components to the fundamental component:

$$THD_I = \sqrt{(\Sigma {I_n}^2, n \geq 2)} / I_1 \tag{2}$$

High THD degrades power quality: it causes additional heating in transformers and conductors, can reduce equipment efficiency and lifespan, and can lead to relay or protection misoperation. Because harmonic injection is a property of the inverter and its control, it is present whenever the inverter is exporting, irrespective of whether the steady-state voltage profile is acceptable.

6.2. The IEEE 519 Standard

IEEE 519, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, is the standard most widely referenced for distribution harmonic limits. It sets limits at the point of common coupling (PCC)—the boundary between the customer installation and the utility—rather than on individual equipment. The most commonly cited headline requirement is that the current distortion at the PCC remain below 5%, with stricter limits on individual harmonic orders that decrease as harmonic order increases. Strictly speaking this limit is the total demand distortion and depends on the ratio of short-circuit current to load current, so on a stiffer system the allowed value can be higher; the 5% figure is the most commonly quoted case and is used as the reference here. Some regional grid codes are more stringent, requiring PV THD below 3%. It is important to note that IEEE 519 governs the aggregate at the PCC, not each device; system integration can push the measured distortion above an individual inverter's nameplate value, which is why harmonic behaviour should be modelled during design rather than discovered at commissioning. Figure 5 shows example harmonic current spectra, where the distortion is concentrated at the lower odd harmonic orders and the overall THD can be substantial.

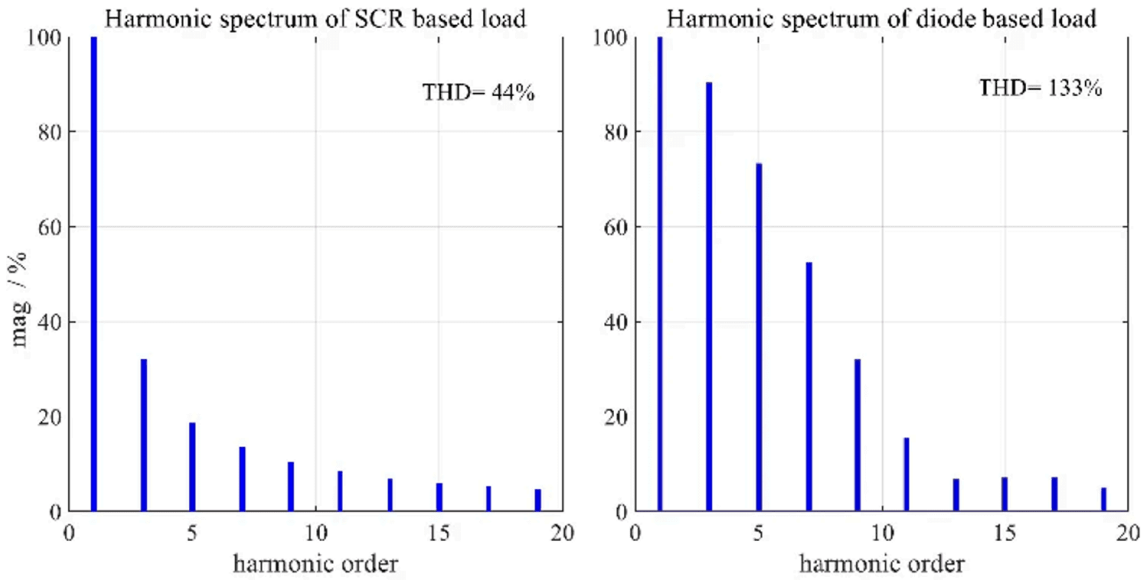


Figure 5. Example harmonic current spectra for nonlinear loads, with total harmonic distortion (THD) of 44% and 133%. Power-electronic devices such as PV inverters inject harmonics in a similar way, which is why the aggregate must be checked against the IEEE 519 limit [13].

6.3. A Caution on Penetration and Harmonics

The literature warns against a misleading conclusion that can arise when inverter harmonics are ignored while nonlinear-load harmonics are modelled: under that incomplete assumption, adding PV can appear to reduce THD, which contradicts hosting-capacity studies that properly account for inverter emission. A complete harmonic assessment must therefore include the harmonic injection of both the nonlinear loads and the PV inverters themselves. This is a concrete example of why “depth of harmonic analysis” is the recurring criticism of impact studies.

6.4. Harmonic Mitigation Techniques

Three families of mitigation are reported in the literature, summarized in Table 3:

- Passive filters: tuned LC branches (and LCL output filters) that present a low-impedance path to specific harmonic orders. They are inexpensive and efficient, but their performance depends strongly on source impedance and they can introduce resonances.
- Active filters: power-electronic devices that sense the harmonic content and inject a cancelling current. They adapt to changing conditions and avoid fixed-tuning resonance problems, at higher cost

and complexity. LCL filters with active damping are a common compromise for inverter outputs.

- Topological solutions: multi-level inverter topologies synthesize a stepped waveform closer to a sinusoid; as the number of levels rises, THD falls monotonically, and high-level designs can meet the IEEE 519 ceiling with little or no passive filtering.

Technique	Strength	Limitation
Passive (LC / LCL)	Low cost, simple, efficient for targeted orders	Source-impedance dependent; resonance risk; fixed tuning
Active filters	Adaptive, broadband cancellation, no fixed-tuning resonance	Higher cost and control complexity
Multi-level topology	Lower THD at source; reduces or removes filtering need	More devices/components; higher converter complexity

Table 3. Comparison of harmonic-mitigation techniques for PV inverters.

7. Inverter-Based Mitigation and IEEE 1547-2018

The inverter is both a source of some impacts and the fastest available tool for managing them. This section reviews how modern “smart” inverters address the dynamic and steady-state voltage problems of Sections 5 and 6.

7.1. From Disconnection to Grid Support

The earlier interconnection standard, IEEE 1547-2003, was written for low penetration and required distributed resources to disconnect during grid disturbances—appropriate when PV was negligible, but counterproductive when PV is a major resource whose simultaneous disconnection would itself destabilize the feeder. The 2018 revision, IEEE 1547-2018, fundamentally changes this posture by enabling and, in many jurisdictions, requiring grid-support functions from the inverter, including voltage and frequency ride-through, voltage and frequency support, and defined ramp-rate settings.

7.2. Volt-Var and Volt-Watt Functions

Two autonomous functions directly target voltage rise. The volt-var function adjusts the inverter's reactive-power output as a function of local voltage, absorbing reactive power when voltage is high. Because of the high R/X ratio of LV feeders, reactive control alone is less effective there than in transmission systems, which motivates the second function. The volt-watt function curtails the inverter's active-power output when voltage exceeds a threshold; since the P·R term dominates the LV voltage-rise relationship, curtailing P is a direct and effective—though energy-wasting—means of limiting overvoltage. Defined ramp-rate settings, newly available under the 2018 standard, additionally limit how fast an inverter increases output, smoothing the recovery ramp after a cloud passes and thereby reducing the dynamic stress of Section 5.

7.3. Coordination Challenges

These functions are not a complete solution. The volt-var and volt-watt responses can interact and, under some settings, produce instability; and because each inverter typically acts autonomously on local measurements, uncoordinated action across many inverters at high penetration can produce adverse interactions that compromise voltage regulation and efficiency. The literature therefore treats inverter settings and their coordination as an active design problem, not a solved one. Dynamic voltage support during abnormal conditions is also not mandated by the 2018 standard, leaving a gap for future revisions.

7.4. Complementary Measures

Where inverter functions are insufficient, the literature reports complementary measures: energy storage to absorb ramps and smooth output, supercapacitors—which have been found particularly effective at suppressing the fastest fluctuations—active-power curtailment at the DC/DC stage, and conventional grid reinforcement. Each trades cost against effectiveness, and the appropriate choice depends on whether the binding constraint is steady-state voltage, fast fluctuation, or harmonics.

8. Results and Analysis

Putting the reviewed literature together with the equations from Section 3, a few main points come out.

8.1. Dynamic Limits Are Often Reached First

Probably the main result is that the limit on how much PV a feeder can take is often reached first because of a dynamic or power-quality problem, not because the steady-state voltage goes out of range. As noted earlier, voltage fluctuation has been reported as problematic from around 40% penetration of local rooftop capacity, and tap-changer over-operation has been seen at penetration as low as 20%. So, a steady-state study could report perfectly acceptable voltages at these penetration levels and still be too optimistic about how much PV the feeder can actually host.

8.2. The Role of the R/X Ratio

The high R/X ratio of distribution lines is what links the steady-state and the dynamic voltage effects together. Because it makes voltage depend strongly on active power, both the steady overvoltage and the fast cloud-driven fluctuation end up being significant in LV networks. It is also the reason reactive (volt-var) control is fairly weak in these networks, and why active-power measures such as volt-watt curtailment or storage tend to be the more direct options. In other words, a lot of the voltage discussion comes back to this one relationship.

8.3. Harmonics as a Separate Problem

Harmonic distortion is a separate issue from the voltage magnitude, and it has to be checked on its own against the IEEE 519 5% PCC limit, including the emission of both the nonlinear loads and the PV inverters. If the inverter emission is ignored, the analysis can give the misleading result that PV improves power quality. The mitigation options are well established—passive, active, and multi-level-topology approaches all exist—but they really need to be designed in from the start rather than added on afterwards.

8.4. Mitigation and Its Limits

IEEE 1547-2018 grid-support functions, together with storage and network reinforcement, can deal with both the voltage and the dynamic problems. The catch is that at high penetration their effectiveness depends on the settings being coordinated, and uncoordinated autonomous action can actually make things worse. So, the real question is not whether the tools exist, but how they are tuned and coordinated —which, once again, is something only time-series and dynamic analysis can really answer.

8.5. Summary Comparison

Table 4 contrasts what a conventional steady-state study captures with what the dynamic and power-quality analysis reviewed here adds.

Aspect	Steady-state load-flow	Dynamic + PQ analysis (this article)
Overvoltage at peak generation	Captured	Captured and explained via $\Delta V \approx (PR+QX)/V$
Cloud-driven voltage fluctuation / flicker	Not captured	Captured (ramp rate, time series)
Tap-changer / capacitor wear	Not captured	Captured (operation counts)
Harmonic distortion vs. IEEE 519	Not captured	Captured (THD, spectrum)
Effective hosting-capacity limit	Over-estimated	Realistic

Table 4. What steady-state analysis captures versus what dynamic and power-quality analysis adds.

9. Conclusions and Recommendations

High photovoltaic penetration affects distribution feeders in ways that extend well beyond the steady-state overvoltage that most impact studies report. This review has shown that two further classes of effect—dynamic voltage behaviour driven by cloud-induced irradiance variability, and harmonic distortion injected by inverters—are both significant and systematically omitted by fundamental-frequency load-flow analysis.

The principal conclusions are: (1) feeder voltage in distribution networks is dominated by active-power injection because of the high R/X ratio, which is captured by the relationship $\Delta V \approx (P{\cdot}R + Q{\cdot}X)/V$ and which underlies both steady and dynamic voltage effects; (2) cloud transients produce fast power ramps that cause voltage fluctuation, flicker, and accelerated wear of regulation equipment, with problems reported from penetration levels as low as 20–40%; (3) inverter harmonic emission is an independent constraint that must be assessed against the IEEE 519 5% PCC limit, including the inverters' own contribution; and (4) IEEE 1547-2018 smart-inverter functions, supported by storage and reinforcement, can mitigate these impacts but require careful, coordinated tuning.

9.1. Limitations

This study is literature-based and analytical; it does not produce original quantitative results for a specific feeder. The numerical thresholds quoted are drawn from studies on particular networks and penetration definitions and should not be read as universal constants. The treatment of the fastest electromagnetic transients is qualitative, since detailed transient simulation is outside the article's scope.

9.2. Recommendations for Future Work

- Complement any steady-state PV-impact assessment with quasi-static time-series simulation at sub-minute resolution, driven by realistic cloudy-day irradiance, to expose voltage fluctuation and equipment-operation counts.
- Perform a harmonic power-flow assessment that includes both nonlinear-load and PV-inverter emission, and verify compliance with IEEE 519 at the point of common coupling.
- Evaluate coordinated IEEE 1547-2018 volt-var and volt-watt settings, with ramp-rate limits, as a mitigation strategy, and quantify the trade-off against energy curtailed.
- Where feeder data permit, model the impact of energy storage or supercapacitors on the worst-case ramp scenarios identified in the first recommendation.

Appendix A. Key Analytical Relationships

A.1. Two-bus voltage rise (distribution approximation): $\Delta V \approx (P \cdot R + Q \cdot X) / V$. With $R/X \approx 4$ in LV networks, the $P \cdot R$ term dominates, so voltage is governed primarily by active-power injection. In transmission ($X \gg R$), the $Q \cdot X$ term dominates instead.

A.2. Power ramp rate: $RR = \Delta P/\Delta t$. Quantifies the speed of PV output change during a cloud transition; the basis of ramp-rate limits in IEEE 1547-2018.

A.3. Total harmonic distortion (current): $THD_I = \sqrt{(\Sigma\, I_n^2,\, n \geq 2)}/I_1$. Compared against the IEEE 519 limit of 5% at the point of common coupling; some grid codes require below 3%.

Abbreviations

The following abbreviations are used in this manuscript:

doi.org/10.32388/UHXYG9

Abbr.	Definition
PV	Photovoltaic
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
OLTC	On-Load Tap Changer
DG	Distributed Generation
LV	Low Voltage
PWM	Pulse-Width Modulation
HC	Hosting Capacity
R/X	Resistance-to-Reactance ratio

Statements and Declarations

Funding

This research received no external funding.

Potential Competing Interests

The authors declare no conflicts of interest.

Author Contributions

Conceptualization, M.B.; investigation, literature review, analysis, and writing—original draft preparation, U.T.; writing—review and editing, U.T. and M.B.; supervision, M.B. All authors have read and agreed to the published version of the manuscript.

Ethics

This study did not involve human participants or animals or require ethical approval.

Data Availability

No new data were created in this study. All data discussed are taken from the cited published sources.

Use of Generative AI

The author used a generative AI assistant (Anthropic's Claude) to improve the language, grammar, and overall structure of the article, and to help organize and refine the text. All technical content, analytical relationships, numerical examples, and conclusions were developed and verified by the authors.

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Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.