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Comprehensive analysis and mitigation of high voltage challenges in grid-connected solar photovoltaic systems for sustainable integration

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ABSTRACT: This study investigates a persistent high voltage issue at a consumer's end in an urban on-grid solar system network located in **Suzuki Colony, Bhilwara, Rajasthan**. Despite the transformer output being within permissible limits, **most of the consumer's net meters recorded unusually high R-phase voltages.** The study identifies the cause of the issue as a result of absence of solar generation's "droop voltage" effect, prevalent in domestic solar systems feeding only a single phase. The paper further elaborates on the phenomenon, analysis methods, and corrective actions taken by utility personnel.

KEYWORDS: AEMO (Australian Energy Market Operator), High Voltage, Droop Voltage, Solar Net Meter, MPPT, On-Grid Solar, Load End Voltage, Phase Imbalance, Distribution Transformer Centre (DTC), Reactive Power Control, Volt-Watt Control, Volt-VAR Control.

I. INTRODUCTION

The increasing penetration of renewable energy sources, particularly solar photovoltaic (PV) systems, into the electrical grid has redefined the dynamics of power generation and distribution. Among these, **grid-connected solar systems** have emerged as a dominant solution for sustainable energy development. As global and national energy policies pivot towards greener technologies, the widespread adoption of solar on-grid systems presents both opportunities and challenges that require in-depth technical and economic assessment. [1]

High Voltage Issues at Load End in On-Grid Solar Systems

One of the most critical operational challenges in solar-integrated grids is the **rise in voltage levels at the consumer or load end**, particularly under **low load and high generation scenarios**. These voltage fluctuations can lead to equipment malfunction, reduced power quality, and possible grid instability.:

The integration of rooftop solar photovoltaic (PV) systems with existing on-grid electrical infrastructure introduces complex challenges, especially in voltage regulation at the load end. This study presents a detailed analysis of one such anomaly observed in Bhilwara, Rajasthan. Despite standard voltage profiles from the Distribution Transformer (DT), the consumer net meters displayed elevated R-phase voltages during daytime hours. The paper explores

- Root causes of over-voltage due to reverse power flow.
- Impact of inverter-based generation on voltage profile.
- Possible mitigation measures such as Volt-VAR & Volt-Watt control, reactive power compensation

Detailed field data, including consumer and distribution transformer (DT) metering information with load survey parameters, was systematically studied and analysed to model voltage profiles and comprehensively evaluate the impact of increasing solar PV penetration on the stability and operational performance of the distribution network.

II. LITERATURE SURVEY

A prominent case study exemplifying the consequences of poor voltage regulation is the **2016 South Australian Grid Blackout**. While the immediate cause of the system-wide outage was attributed to a series of weather-related





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transmission line failures, subsequent analysis by the Australian Energy Market Operator (AEMO) pointed to critical issues with solar inverter ride-through settings and voltage regulation. Many rooftop solar inverters were observed to disconnect or reduce output in response to transient voltage events, which compounded the instability of the network during a vulnerable period [2]. Furthermore, the prevalence of smart inverters without coordinated Volt-VAR control exacerbated the local voltage rise, particularly in suburban feeders with high solar penetration but insufficient reactive power support.

AEMO's analysis revealed that nine of the 13 wind farms online at the time did not ride through the six voltage disturbances, leading to a significant loss of generation capacity. Preliminary discussions with wind farm operators indicated that this inability to ride through was due to voltage ride-through settings configured to disconnect or reduce turbine output when a certain number of disturbances were detected within a defined time period. The report also acknowledged that the growing proportion of inverter-connected generation, such as rooftop solar systems, contributed to lower system inertia, making the grid more susceptible to frequency instability during such disturbances [2]

In another thesis of Mahmud, Nasif named "High penetration of solar photovoltaics into low-voltage distribution **networks: developing novel feeder voltage control strategies**." The thesis analysed feeder-level data from the New South Wales and Victoria regions, observing that voltage rise in excess of 255 V (230 V +10%) was a frequent occurrence in areas with PV penetration above 30%. The authors concluded that traditional voltage control mechanisms, such as on-load tap changers (OLTCs) and capacitor banks, are insufficient in the context of highly variable and decentralized generation. [3]

III. METHODOLOGY

The investigation began with a site visit following a high voltage complaint (No. 001HVS24032873XX) in Suzuki Colony, Bhilwara. Voltage measurements at the consumer's net meter showed an unusually high R-phase voltage of 278.5V, while Y and B phases remained within normal limits. However, the corresponding Distribution Transformer (DT No. 170) voltages were within permissible limits (245–250V), confirmed through both field tests and a 90-day AMR load survey. No issues were found in earthling or neutral connections, ruling out utility-side faults.

Further analysis revealed that the high R-phase voltage occurred only during daytime and was limited to consumers with rooftop solar systems—11 out of 22 connected to the same DT. All solar inverters were single-phase, injecting power into the R-phase, causing localized voltage rise due to absence of droop control. The MPPT algorithm in these inverters maintained high output voltages (270–280V) to prioritize solar export. Without Volt-Watt or Volt-VAR control, the inverter output exceeded grid voltage, leading to overvoltage conditions.

• Conceptual Illustration of Supply Voltage Preferences decided by Net Meter



(a) Water Tank Analogy

Consider Two tanks named "A" & "B" having same capacity connected to each other & at the centre drilling is done & tap "C" is attached.

Scenario 1st: When both A & B tanks are filled with same level having same potential **Result: Water Won't go to Tap-C**

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Scenario 2nd: When Tank-A have high level compared to Tank-B (Water will flow from High potential to Low (From A to B))

Result: Water will go to Tap-C from Tank -A

Scenario 3rd: When Tank-B have high level compared to Tank-A (Water will flow from High potential to Low (From B to A))

Result: Water will go to Tap-C from Tank-B



(b) Conceptual illustration of how supply voltage is get to Net Meter

Scenario 1st: When both DT Meter & Generation Meter having same voltage level **Result: Net Meter won't get supply from either DT Meter or Generation Meter**

Scenario 2nd: When DT Meter having high Voltage (Potential) compared to generation meter **Result: Net Meter get supply through utility DTC (during Night Time Scenario)**

Scenario 3rd: When Solar Generation Meter having high Voltage(Potential) compared to DTMeter

Result: Net Meter get supply through Solar Generation Meter (during day Time Scenario)

IV. EXPERIMENTAL RESULTS

Problem Statement: A complaint (Complaint No. 001HVS24032873XX) was logged on **March 28, 2024**, by consumer **K_NO 110212033XXX** located at **Suzuki Colony, CSD-II**, regarding persistent high voltage issues. The voltages at the net meter reached up to **278.50V** on R-phase, affecting equipment performance & failure in operation.

Site and Technical Data Overview

After Lodging the complaint NPC team reached the site with proper data as Follows:

- 1. Distribution Transformer (DT) Details
- Substation: 33kV AZAD NAGAR
- Feeder: 11kV AZAD NAGAR
- DT No.: 170, Rating: 200 kVA, 3 Phase
- Type: Urban
- CT Ratio: 400/5
- Cable: 3.5 Core
- DT Meter S/N: X0504176





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- 2. Consumer Meter Details
- Consumer No: **110212033XXX**
- Net Meter S/N: X2178152
- Generation Meter S/N: X2130612
- Connection Type: Domestic (DS)
- Distance from DTC: ~200 meters

Observations and Measurements: Consumer Net Meter Voltage (X2178152) Checked by NPC Team by both tong tester and in meter display for cross verification. R-Y-B Phase voltages of Net Meter are

R Phase Voltage: **278.50 Volt** Y Phase Voltage: 237.12 Volt B Phase Voltage: 248.43 Volt



(a) R Phase Voltage of X2178152

(b) Y Phase Voltage of



(c) B Phase Voltage of X2178152

It is observed that R phase voltage of Meter is very high compared to other Y & B phases.

DT meter Voltages (X0504176) Phase to Phase (P-P) & Phase to Neutral (P-N) are also checked for **off load & on load conditions.** R-Y-B Phase to Phase & Phase to Neutral voltages are R-N Voltage : 247.7 Volt ; R-Y Phase Voltage : 423 Volt





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Y-N Voltage : 244.7 Volt ; Y-B Phase Voltage : 427 Volt B-N Voltage : 246.9 Volt; B-R Phase Voltage : 425 Volt

All the DT meter voltages are found within limit for off load & on load conditions.Earthing of DTC is also checked; found ok.



(d) Phase to Phase & Phase to Neutral Voltages of DT Meter X0504176

After all Conditions are found ok neutral cables from both terminals are checked for carbon accumulation. Neutral jumpers at cut points are also checked for Neutral cut/Neutral Burnt/Carbon Accumulation. All conditions are found ok DT Meter (X0504176) Load Survey is also checked through AMR system. R-Y-B Phase to Neutral Voltages are analysed at the same time through MRD. During MRD analysis it is found that DT voltages of all three phases are found within permissible limits (in the range of 245 Volt -250 Volt) never crossed 250 Volt limit in past three months (90 days Load Survey) creating a never seen situation on the field which are mentioned below:

Even though DT Meter (X0504176) voltages never crossed the **250 Volt** level for all three phases for past 90 days but Consumer Meter (X2178152) R phase showing **278 Volt** fed from the same DT which is 200 Meters away consumer service. In general condition Voltage drops with increase in distance but we are facing some unusual situation where **DT voltages are 250 Volt & Consumer Service Voltage is 278 Volt.** (Vs > V_R in on load condition)

Such type of conditions is only observed either at No load conditions creating Ferranti Effect (Receiving End Voltage > Sending End Voltage) or huge capacitive load presence at the consumer premises but since Consumer category is Domestic most of the load present is resistive type [4]



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(e) DT Meter (X0504176) voltages never crossed the 250 Volt level for

When Solar Comes into picture everything is resolved!!!

After checking other consumers meter voltages, we found unique pattern that R phase voltages of most of the consumers having high voltages compare to other two phases (in the range of 270-280 Volt) after connecting the dots it is found that all these consumers are mostly solar consumers.

After analysing consumer base of DTC out of 22 consumers connected to DTC 11 consumers having Solar installed. After checking both generation meter voltage & Net meter voltage it is concluded that the high voltage problem is not from utility (DTC) end but solar generation end causing high voltage problems

K_NO	Meter Status	CAT	METER_SERIAL_NUMBER	Generation Meter	DT_STICKER_ID
110212016XXX	Net meter	DS	X1463660	X1223258	170
110212016XXX	Net meter	DS	X2178293	MB00004763	170
110212016XXX	Net meter	DS	X1999014	X0509355	170
110212016XXX	Net meter	DS	X1999041	MB00052275	170
110212016XXX	Net meter	DS	X1223187	7543480	170
110212033XXX	Net meter	DS	X2178152	X2130612	170
110212016XXX	Net meter	DS	X2178301	X2130580	170
110212016XXX	Net meter	DS	X1680385	MB00095510	170
110212016XXX	Net meter	DS	X1999034	MB00097532	170
110212016XXX	Net meter	DS	X1680433	MB00097593	170
110212027XXX	Net meter	DS	X1999005	MB00097542	170

(f) Solar Consumer Details of DT No. 170 (Suzuki

During analysis it is found that R phase voltage are high only during day-time since during day time all the generation is carried through R phase (Generation meter R phase voltages are very high) therefore during day time net meter is fed from solar generation & during night time net meter fetch supply from utility end since solar generation is not possible during night time. After analysing all net meters & generation meters it is observed that high voltages are generated through solar generation not through utility supply. Other consumers net meter & generation meter is also showing same results.





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Notable Observation: Despite normal voltage levels at the transformer, high R-phase voltage was observed at the consumer end only during daytime (9 AM-6 PM) since high voltages are generated through solar generation not through utility supply.



(g) R Phase Voltage level of X2178152 is



(h) R Phase Voltage level of X2178152 is Very high only during day time (9 am to 6 pm)



(i) X2130612 (Generation meter) Showing high voltage on R phase since generation is only carried





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(j) MB00004763 (Single Phase Generation) Meter generating High voltage during day

V. CONCLUSION

When solar generation feeds back into the grid, especially via single-phase systems, the local voltage on that phase can rise above the transformer output. This is due to absence of **droop voltage control strategies [5][6]** (a control mechanism in solar inverters to optimize the voltage levels well within permissible limit) in Solar PV inverter which are commonly installed for **Small-scale rooftop solar systems** (residential, <10 kW)

The second reason is MPPT (Maximum Power Point Tracking) algorithms in solar inverters were set to maintain a high output voltage (prioritize generation delivery when solar voltage > grid voltage) often in the range of 270–280V, on the R-phase to provide maximum generation & benefit consumer & also for avoidance from tripping of inverter circuit if its voltage is below the utility supply voltage. This resulted in:

- Overvoltage on R-phase during generation hours
- Load equipment malfunctioning due to voltage imbalance
- Household Electrical Wiring also get affected & possibility of burnt

Solution Implementation

- 1. **Phase Transposition**: At utility level, phases were transposed to balance voltage levels.
- 2. Vendor Coordination:
 - o Instructed to distribute solar generation across all three phases.
 - o Recommended lowering output voltage of inverters Well within range of 255 Volt-265 Volt.
- 3. Advanced Inverter Controls:
 - Adoption of Watt-Volt (P-V) and Watt-VAR (P-Q) droop control Inverters.[7]
 - Reactive power modulation to mitigate overvoltage scenarios.





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