Energy Proceedings
Vol 66, 2026
ISSN 2004-2965

Feeder-Level Impact Assessment of Rooftop Solar Integration in Distribution Networks

Rishu Garg[1*], Hanumanth Raju G V[1], Stalon Jessin[1,2]

1 Centre for Study of Science, Technology, and Policy, Bengaluru, India

2 Department of Electrical Engineering, National Institute of Technology Calicut, Kozhikode, India

(Corresponding Author: rishugarg@cstep.in)

ABSTRACT

Indian distribution companies are undergoing significant structural and operational changes, driven by rising electricity demand and increasing penetration of distributed renewable energy (DRE) sources. Yet, large-scale DRE integration exposes distribution networks to challenges such as intermittency and peak load management. This study addressed these issues by virtually modelling a practical sub-11 kV distribution network in power simulation software using load-flow analysis. It evaluated the infrastructure readiness to accommodate future load growth with DRE integration, ensuring a smooth and sustainable transition.

Based on the model, active power and reactive power losses were determined, and transformers at risk of exceeding their rated loading during peak demand were identified. The findings indicated the threshold levels of rooftop photovoltaic penetration beyond which network reinforcement (such as transformer upgrades, voltage regulation, and reactive support) is essential. This study provides actionable guidance for distribution companies, demonstrating not only the benefits of DRE but also the tipping points at which proactive grid investment becomes mandatory to maintain reliability.

Keywords: Distributed renewable energy resources, power simulation software, energy transition, load-flow analysis, distribution transformers

NOMENCLATURE

Abbreviations	
DISCOMs	Distribution Companies
DRE	Distributed Renewable Energy
FY	Financial Year
DT	Distribution transformers
CAGR	Compound Annual Growth Rate
RTPV	Rooftop photovoltaic

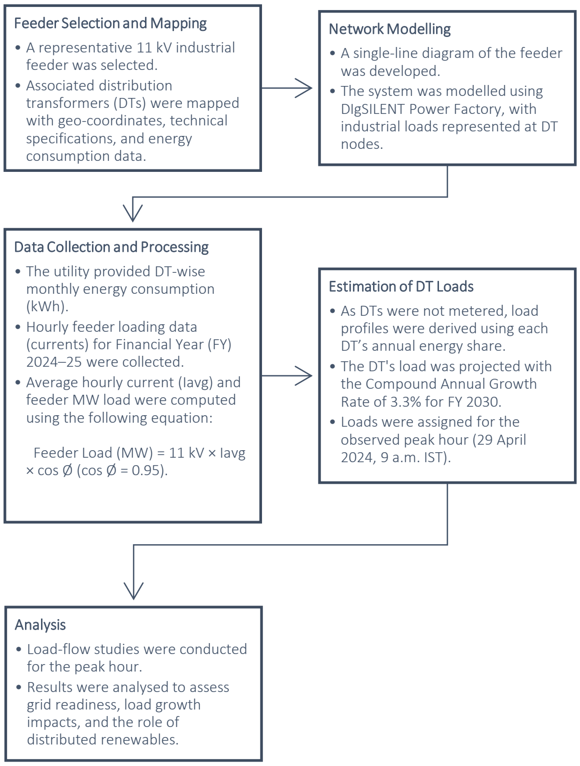
1. INTRODUCTION

India has committed to net-zero emissions by 2070 and has already exceeded its goal of 50% renewable energy in the installed capacity mix. Solar power dominates India's renewable energy mix, with rooftop photovoltaic (RTPV) systems contributing nearly 17% (Ministry of New and Renewable Energy 2025) of solar capacity, underlining the growing role of distributed renewable energy (DRE). For distribution companies (DISCOMs), it is therefore critical to proactively strengthen and adapt their networks to accommodate increasing DRE capacity, ensuring a smooth transition from traditional bulk generation procurement to a decentralised supply. This paper aimed to assess the impact of DRE integration at the distribution voltage level (typically 11 kV and below in India's retail electricity system) and provide practical and implementable recommendations to enhance grid operations and reliability.

This study was undertaken for an Indian DISCOM, which provided access to technical datasets and facilitated field-level support, thereby enabling a comprehensive and practically grounded assessment of the distribution network.

2. METHODOLOGY AND DATA ASSESSMENT

2.1 Methodology



Feeder Selection and Mapping

- A representative 11 kV industrial feeder was selected.
- Associated distribution transformers (DTs) were mapped with geo-coordinates, technical specifications, and energy consumption data.

Network Modelling

- A single-line diagram of the feeder was developed.
- The system was modelled using DIgSILENT Power Factory, with industrial loads represented at DT nodes.

Data Collection and Processing

- The utility provided DT-wise monthly energy consumption (kWh).
- Hourly feeder loading data (currents) for Financial Year (FY) 2024–25 were collected.
- Average hourly current (Iavg) and feeder MW load were computed using the following equation:

Feeder Load (MW) = 11 kV × Iavg × cos Ø (cos Ø = 0.95).

Estimation of DT Loads

- As DTs were not metered, load profiles were derived using each DT's annual energy share.
- The DT's load was projected with the Compound Annual Growth Rate of 3.3% for FY 2030.
- Loads were assigned for the observed peak hour (29 April 2024, 9 a.m. IST).

Analysis

- Load-flow studies were conducted for the peak hour.
- Results were analysed to assess grid readiness, load growth impacts, and the role of distributed renewables.

Fig. 1 Overview of the study methodology

The methodology adopted for this study is outlined in Figure 1. A detailed empirical simulation of an 11 kV industrial feeder, located within city limits and equipped with 23 distribution transformers (DTs), was performed using one full year (8,760 hours) of demand data for Financial Year (FY) 2024–25. Three scenarios were modelled: (i) baseline for 2025, (ii) projected demand growth with a 3.3% compound annual growth rate (CAGR) for 2030, and (iii) 2030 with RTPV offsetting total demand by 80%.

The feeder was traced from its origin at a 33/11 kV distribution substation, and the associated DTs were identified along with their geo-coordinates, technical specifications (such as kVA ratings and monthly energy consumption in kWh), and inter-DT feeder lengths (in metres).

Based on these inputs, a single-line diagram of the distribution network was prepared and modelled using DIgSILENT Power Factory simulation tool. The connected industrial loads were represented as lumped loads at each DT node. For the future year assessment, RTPVs were assumed to be installed at each DT location and modelled collectively as a single cumulative system.

Load-flow analysis was then performed for the peak-hour instant for three representative scenarios, and the results were examined.

2.2 *Calculations*

DT-wise monthly energy consumption (kWh) data, aggregated across all industrial consumers connected to each transformer, along with hourly feeder loading data (phase-wise currents in amperes) for all 365 days of the FY 2024–25, were collected. The average hourly current (I_{avg}) was computed, and feeder loading in MW was estimated for the collected datasets using the following equation:

$$\text{Feeder Load (MW)} = 11\text{ kV} \times I_{avg} \times \cos Ø,$$

where the power factor (cos Ø) was assumed to be 0.95.

Owing to the unavailability of metered data for DTs, the peak-hour loading profiles (MW) contributing to the cumulative feeder peak load were estimated. For this purpose, the annual energy share of each DT was used as a weighting factor and applied to the feeder's peak hour loading for the recorded peak day (29 April 2024, 9 a.m. IST). Two DTs, when allocated peak by energy share, exceeded their safe loading limit (e.g. >100% of kVA at PF 0.95), which is not operationally realistic. Hence, we allocated the feeder peak to each DT in proportion to its annual energy and then capped each DT at its safe loading limit (115% for the two largest DTs and 95% for all others, both at 0.95 PF). Any excess was redistributed to uncapped DTs, prioritising those with higher energy consumption so that the total allocation matched the feeder peak.

This approach enabled us to assign connected loads to each DT in the simulation model and conduct a realistic assessment of distribution network performance under peak conditions.

3. DISTRIBUTION NETWORK MODELLING USING THE POWER SIMULATION TOOL AND SCENARIOS CONSIDERED

This study was conducted using the DIgSILENT Power Factory simulation tool, with instantaneous peak-hour load-flow analysis forming the core of the assessment. The modelled network extended from the 33/11 kV substation down to the DT level (a total of 23 DTs observed on this feeder).

The substation, comprising (8 × 1) MVA and (5 × 1) MVA power transformers operating in parallel, was represented with its technical ratings. Multiple 11 kV feeders emanate from this substation; for this study, one dedicated industrial feeder was selected. These feeders transmit electricity at 11,000 V from the substation to DTs, which step down the supply to 440 V for small-scale industries (16 out of 23 DTs). In contrast, certain heavy industries receive the supply directly at 11,000 V (7 out of 23 DTs) based on their requirements. Both configurations were modelled using field-verified information.

The hourly feeder loading records for all 8,760 hours of FY 2024–25 was analysed, with DT loads assigned in MW for the identified peak hour, as detailed in Section 2.2. Load-flow analysis was then performed for the baseline 'BAU 2025' scenario.

Subsequently, demand forecasts were generated for each DT under the 'BAU 2030' scenario, applying a 3.3% CAGR. In the third scenario, 'BAU 2030 with RTPV', the potential integration of RTPV systems was considered. These DRE generators were modelled at load centres, and the corresponding solar generation profiles were created for the peak hour (29 April 2029, 9 a.m. IST). These inputs were then incorporated into the simulation framework.

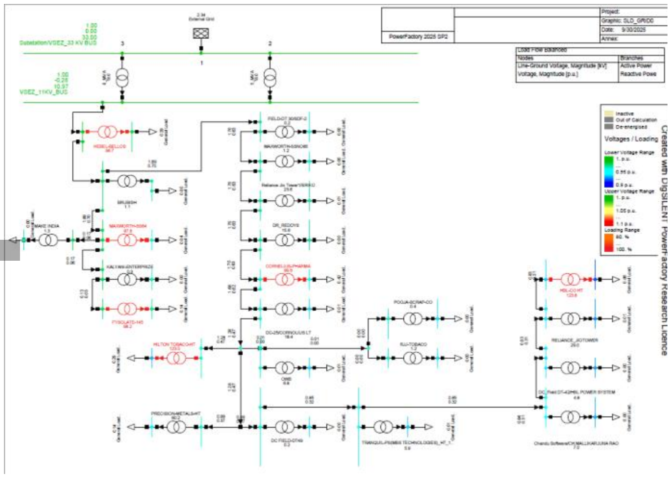


Fig. 2 Single line diagram of the selected 11 kV industrial feeder

This study evaluated three scenarios:

a. BAU 2025 – The practical distribution network was modelled under existing conditions.
b. BAU 2030 – Future energy demand at each DT was projected to FY 2030, with a 3.3% CAGR across all DTs. The updated DT loading was incorporated into the network model, and quasi-dynamic load-flow analysis was performed.
c. BAU 2030 with RTPV – Integration of RTPVs for each DT was modelled as a cumulative RTPV plant, with local load compensation assessed by RTPV meeting 80% of the total DT demand.

4. RESULTS

The results from all three scenarios are summarised below.

Scenarios	**External networks, active power (MW)**	**External networks, reactive power (Mvar)**	**External networks, apparent power (MVA)**
BAU 2025	2.2	0.8	2.3
BAU 2030	2.6	1	2.8
BAU 2030 with RTPV	1.3	0.5	1.4

Table 1. External network system behaviour

Scenarios	**Loads, active power (MW)**	**Loads, reactive power (Mvar)**	**Loads, apparent power (MVA)**
BAU 2025	2.1	0.7	2.2
BAU 2030	2.5	0.8	2.6
BAU 2030 with RTPV	2.5	0.8	2.6

Table 2. Load's system behaviour

Scenarios	**Losses, active power (MW)**	**Losses, reactive power (Mvar)**
BAU 2025	0.1	0.1
BAU 2030	0.1	0.2
BAU 2030 with RTPV	0.0	0.1

Table 3. Summary of system losses

In the base case scenario (2025), the external network recorded an active power of 2.2 MW, a reactive power of 0.8 Mvar, and an apparent power of 2.3 MVA at the peak instant, compared to the load's active, reactive, and apparent power of 2.1 MW, 0.7 Mvar, and 2.2 MVA, respectively. This indicates system losses of 0.1 MW (active) and 0.1 Mvar (reactive), and at the same instant, six DTs were overloaded. Apart from these, all other elements of the network were found to be within permissible voltage limits. Similarly, under the BAU 2030 and BAU 2030 with RTPV scenarios, the total system losses were recorded as 0.1 MW active power and 0.2 Mvar reactive power in the BAU 2030 case and 0 MW active power and 0.1 Mvar reactive power in the RTPV scenario.

5. DISCUSSION

The results clearly indicate that under the BAU 2025 (present) system condition, six DTs were loaded beyond 90% of their capacity, while all conductor segments remained within permissible limits. By FY 2030, with increased DT loadings, the voltage profile of tail-end DTs deteriorates with higher reactive power losses. Hence, upgrading DT capacities and enhancing conductor carrying capacities are necessary. However, when distributed solar generation is integrated at each DT level, the local load is effectively compensated. Compensating 80% of the load for each DT through RTPV systems was identified as the most feasible cap. This is evident from the reduced grid draw of only 1.3 MW active power and 0.5 Mvar reactive power, compared to 2.6 MW active power and 1 Mvar reactive power without RTPV. System losses also decline significantly (0 MW active power and 0.1 Mvar reactive power), with only two DTs overloaded instead of six, and the voltage profile of tail-end DTs also improves. This demonstrates that integrating RTPV systems can enable DISCOMs to defer or avoid network upgradation requirements.

6. CONCLUSIONS

The study highlights that DRE integration, particularly RTPV systems, can substantially reduce active and reactive power losses while alleviating transformer overloading in distribution networks. Simulation results for a practical 11 kV feeder demonstrate that localised generation effectively offsets demand, improves voltage stability, and reduces dependency on the external grid. These insights provide a quantitative basis for DISCOMs to plan grid modernisation and DRE integration strategies, enabling them to extend these approaches across their distribution network systems and support a reliable, efficient, and sustainable transition towards India’s net-zero energy future.

REFERENCES

[1] Ministry of New and Renewable Energy. 2025. Programme/Scheme Wise Cumulative Physical Progress as on 31st August, 2025. Ministry of New and Renewable Energy, August. https://mnre.gov.in/en/physical-progress/.