

Impacts of reverse power flow on substation transformers

Fourth Meeting: WG PC57.133



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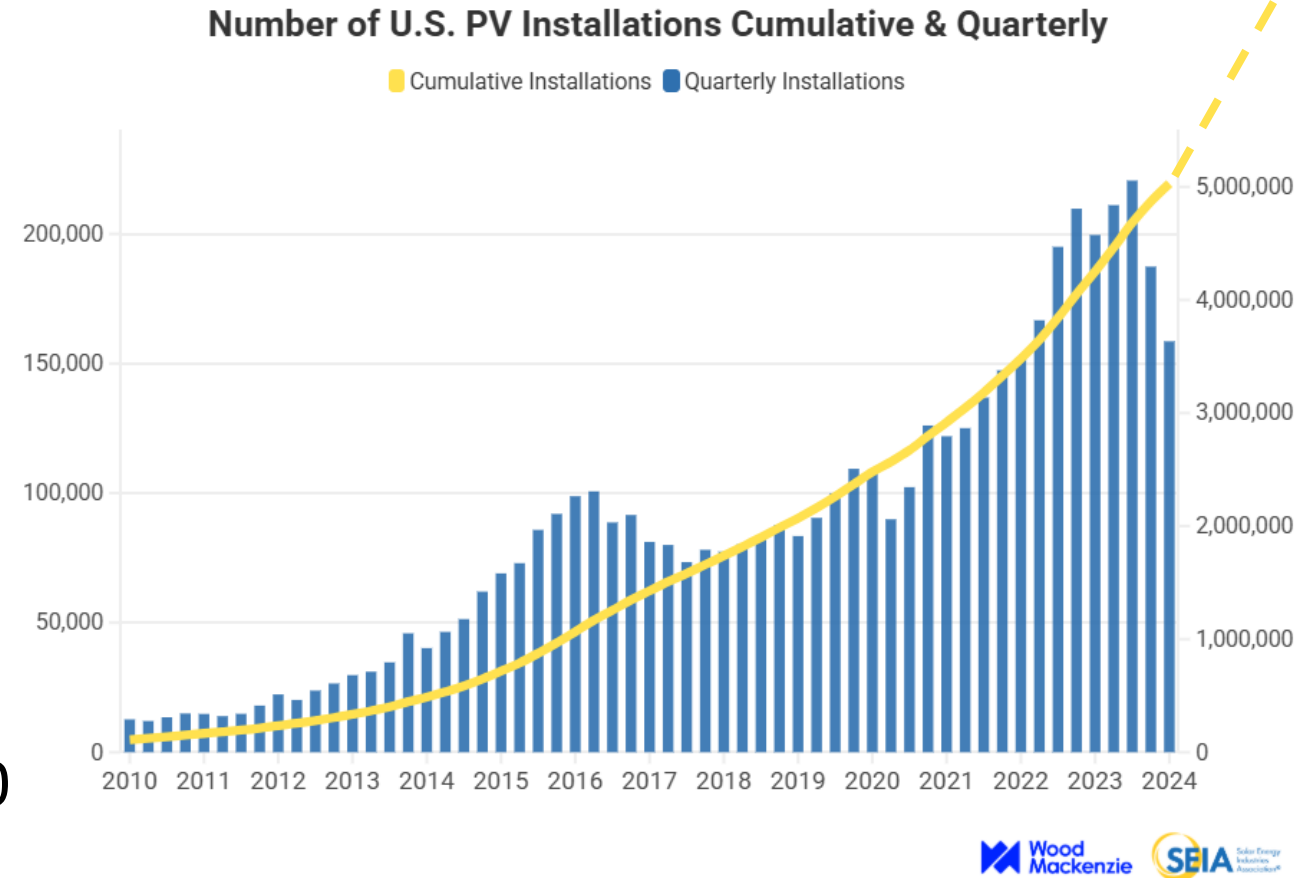
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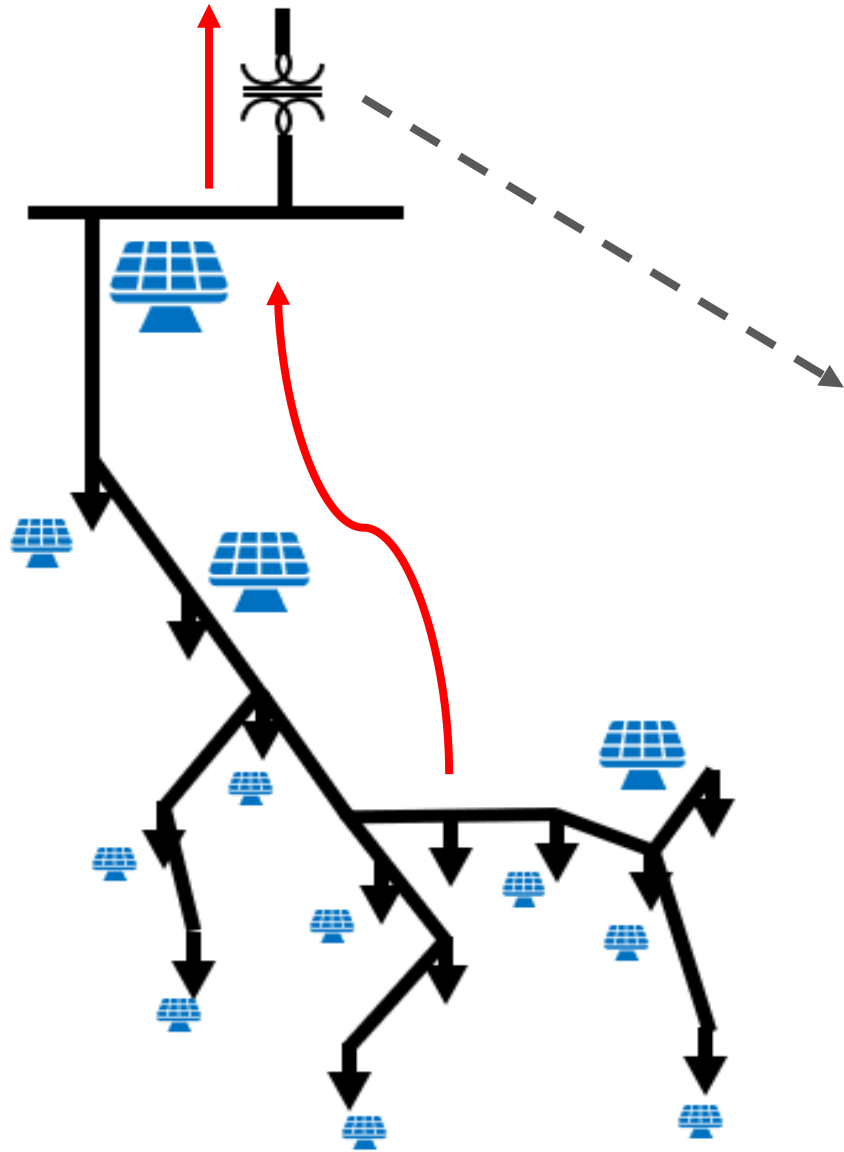
DER penetration is growing...

- Number of solar installations in the U.S.
 - 5 million in 2024
 - 10 million by 2030
 - 15 million by 2034
- Solar generation capacity in the U.S.
 - Half of new generation in 2023
 - Largest generation source by 2050

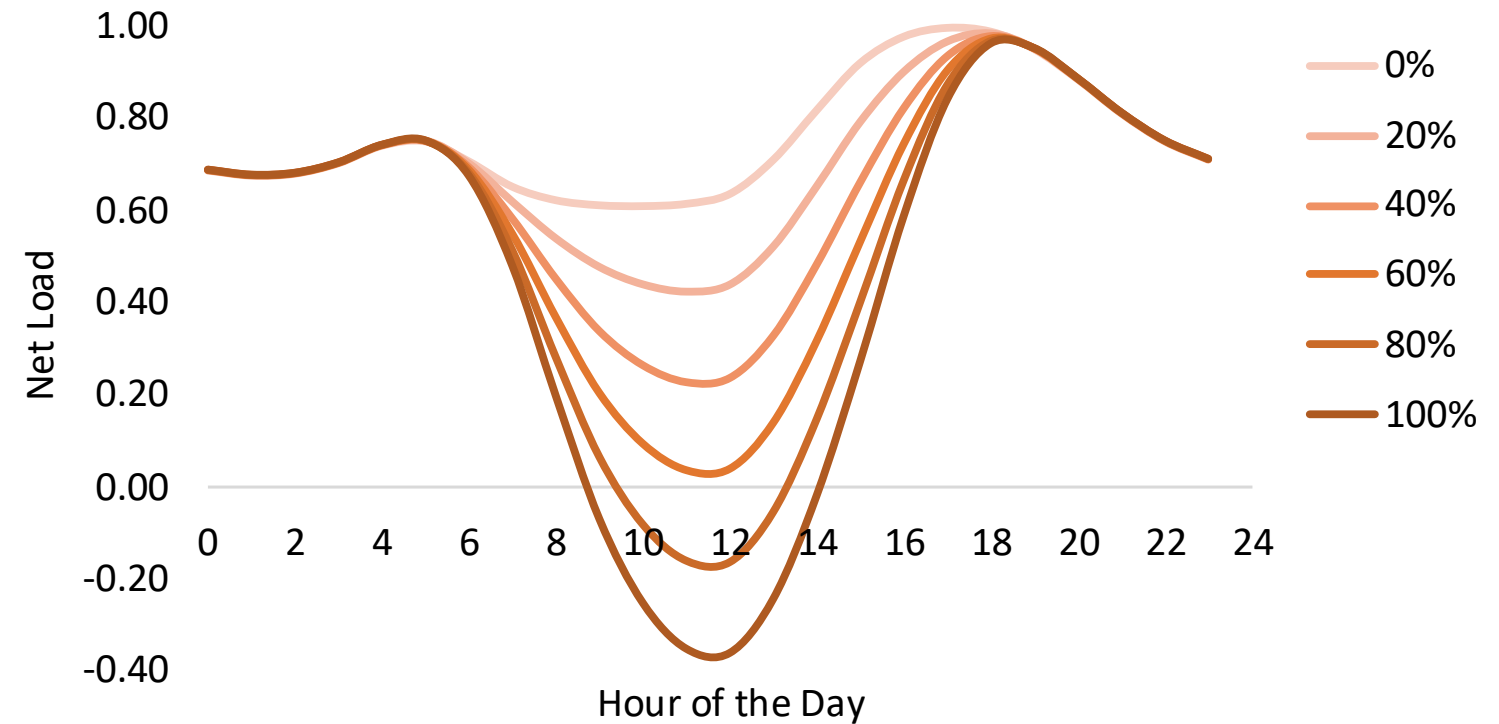


Source: Solar Energy Industries Association. 2025. <https://seia.org/5m/>

Increasing DER generation results in reverse power flows...

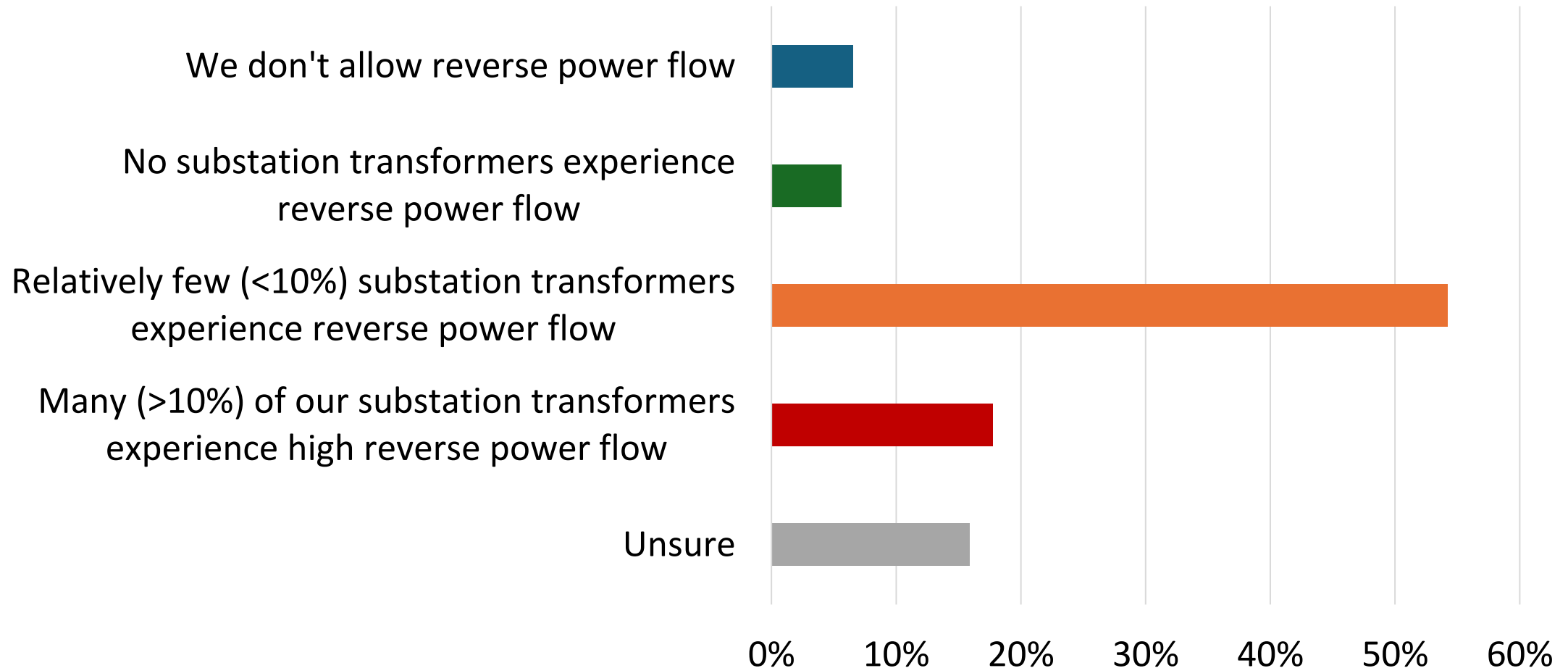


Load Flow Through a Substation Transformer During a Sunny Day



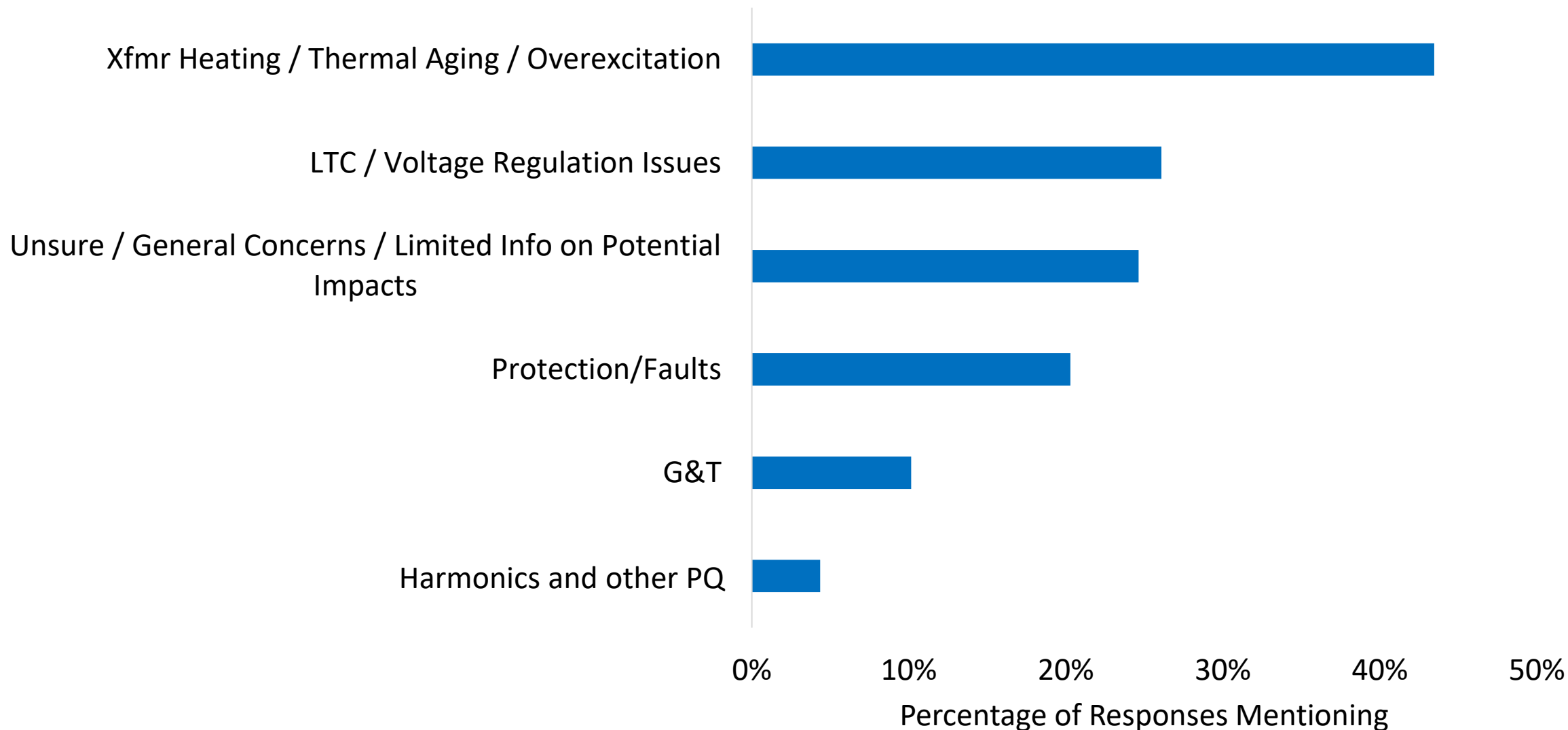
Utilities are increasingly experiencing reverse power flow through substation banks

If reverse power flow is allowed, how common is reverse power flow experienced across your system?





Source: *The Effect of Reverse Power Flows on Substation Transformer Banks: Review of Industry Practices and Literature, Field Data Analysis, and Rating Impacts* - <https://www.epri.com/research/products/000000003002030664>

Top Concerns from Utility Member Survey




Source: *The Effect of Reverse Power Flows on Substation Transformer Banks: Review of Industry Practices and Literature, Field Data Analysis, and Rating Impacts* - <https://www.epri.com/research/products/000000003002030664>

Literature Review


1. E. J. Aladesanmi and D. G. Dorrell, "Investigation and Assessment of the Impacts of Reverse Power Flow on Power System Network Loading under High Penetration of Wind Energy," in IEEE Southern African Universities Power Engineering Conference, Bloemfontein, South Africa, 2019.
 


Overloading simply because excessive reverse power from renewable generation

Analysis based on extreme operating condition:

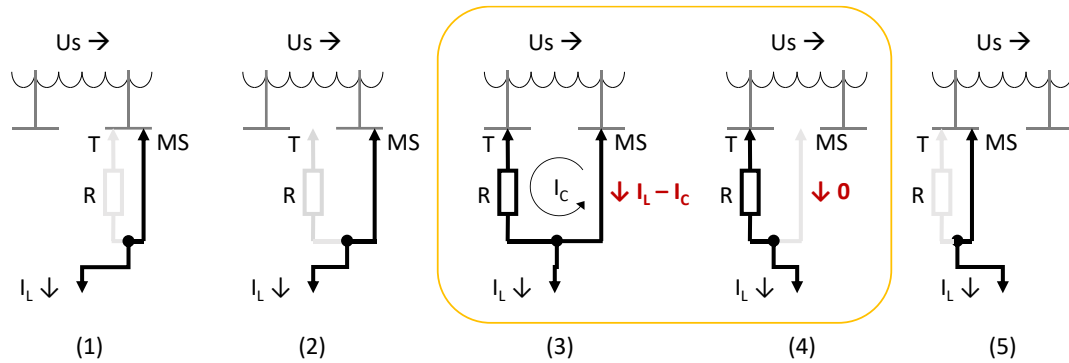
 - $P=133\%$ (reverse)
 - $PF=0.8$ (capacitive)
2. I. Babatunde Majeed and N. I. Nwulu, "Impact of Reverse Power Flow on Distributed Transformers in a Solar-Photovoltaic-Integrated Low-Voltage Network," *Energies*, vol. 15, no. 23, 2022.
3. P. Upadhyay, J. Kern and V. Vadlamani, "Distributed Energy Resources (DERs): Impact of Reverse Power Flow on Transformer," in CIGRE, Paris, France, 2020.


Potential concerns in certain transformer designs:

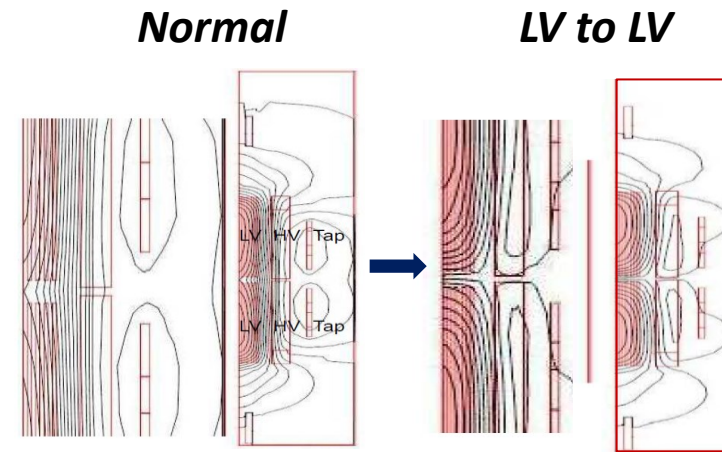
 - Asymmetric LTC diverter circuit
 - One HV – Dual LV (windings are axially split)
4. Reverse Power Flow Impact on Transformers, IEEE Transformer Committee Spring 2021 Meeting, April 29, 2021.
5. E. G. Tenyenhuis, "Reverse Power Flow Impacts for **Legacy Power Transformers**," in CIGRE, Paris, France, 2022.


Conclusion: transformer core loss may see slight increase due to higher voltage rise
6. J. P. P. Perin, N. K. Neto, L. H. Medeiros and V. Bender, "Analysis of Core Losses in a Three-Phase Distribution Transformer Under Reverse Power Flow Using the **Finite Element Method**," in Seminar on Power Electronics and Control (SEPOC), 2023.


More Details on the Potential Concerns (Reference 4, 5)



- Certain UK transformers from 40 years ago used special resistive LTC design with asymmetrical pennant cycle operation
- Under reverse power, the diverter circuit sees increased breaking current that may cause accelerated wear and tear



Picture source:

- Legacy transformers with One HV – Dual LV windings may be designed for step-down operation only
- Changing the power flow direction may result in different leakage flux distribution hence increase loss

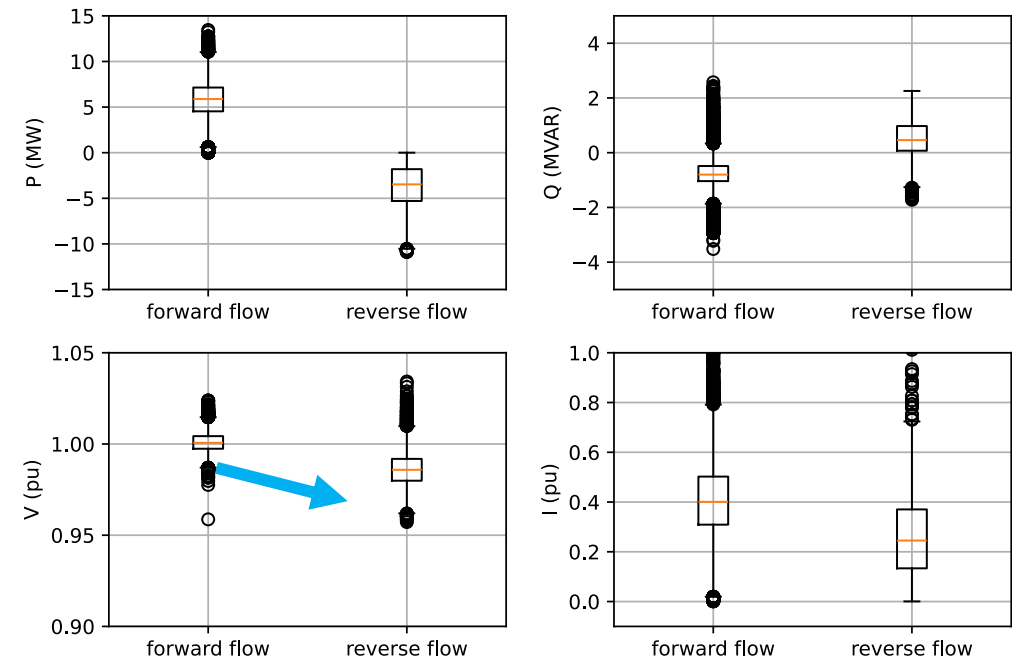
No discussed issues in literatures on two winding transformers

Analysis of Transformer Field Data

- Data of 27 transformers from 4 utilities
- Most are year long with hour interval
- Some are month long with minute interval
- These data are analyzed first with priority
 - Transformers experiencing significant reverse power flow
 - Transformers with factory test reports provided
 - Data contains complete information of ambient temperature, top oil temperature, hot spot temperature, power flow, and LTC tap position

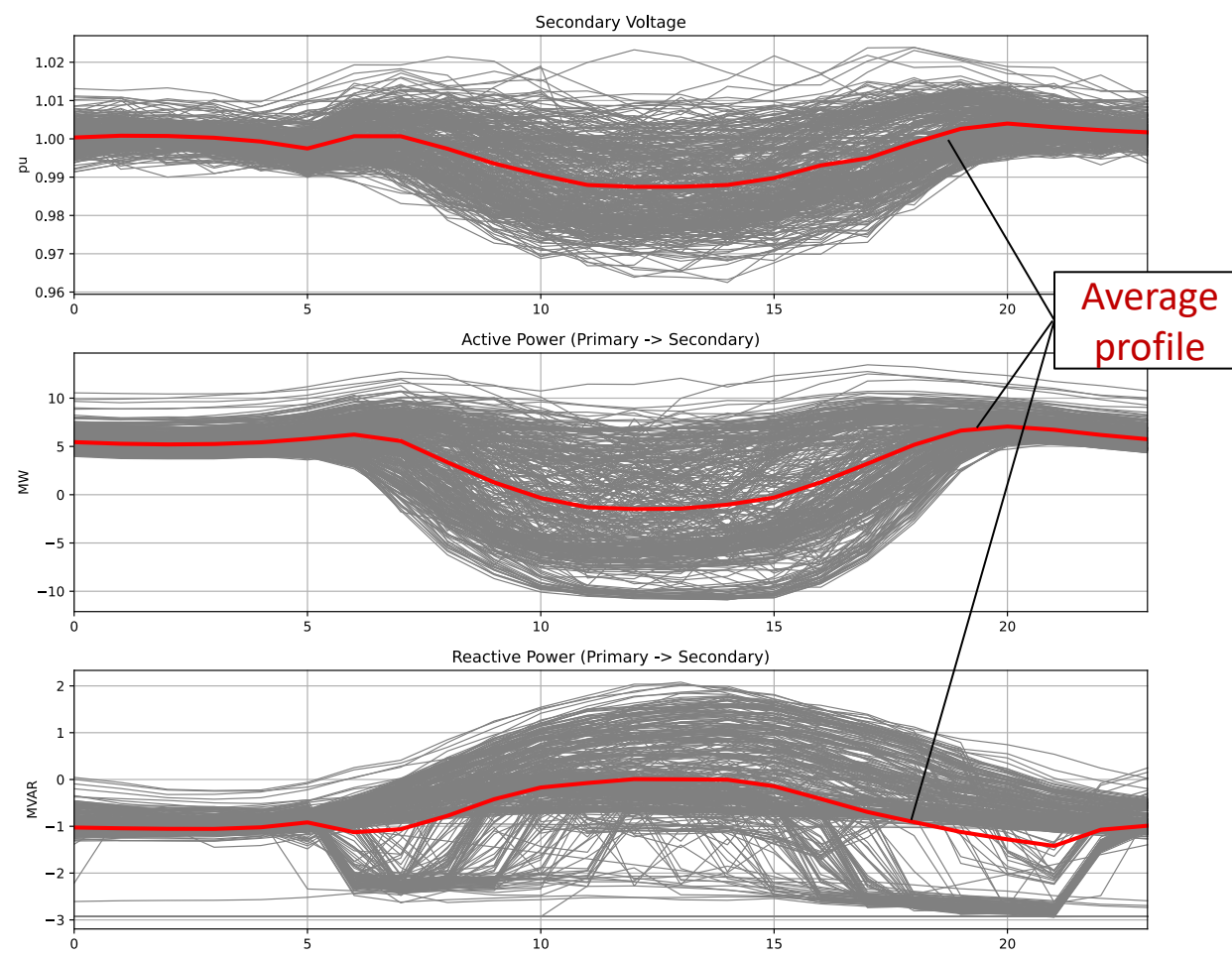
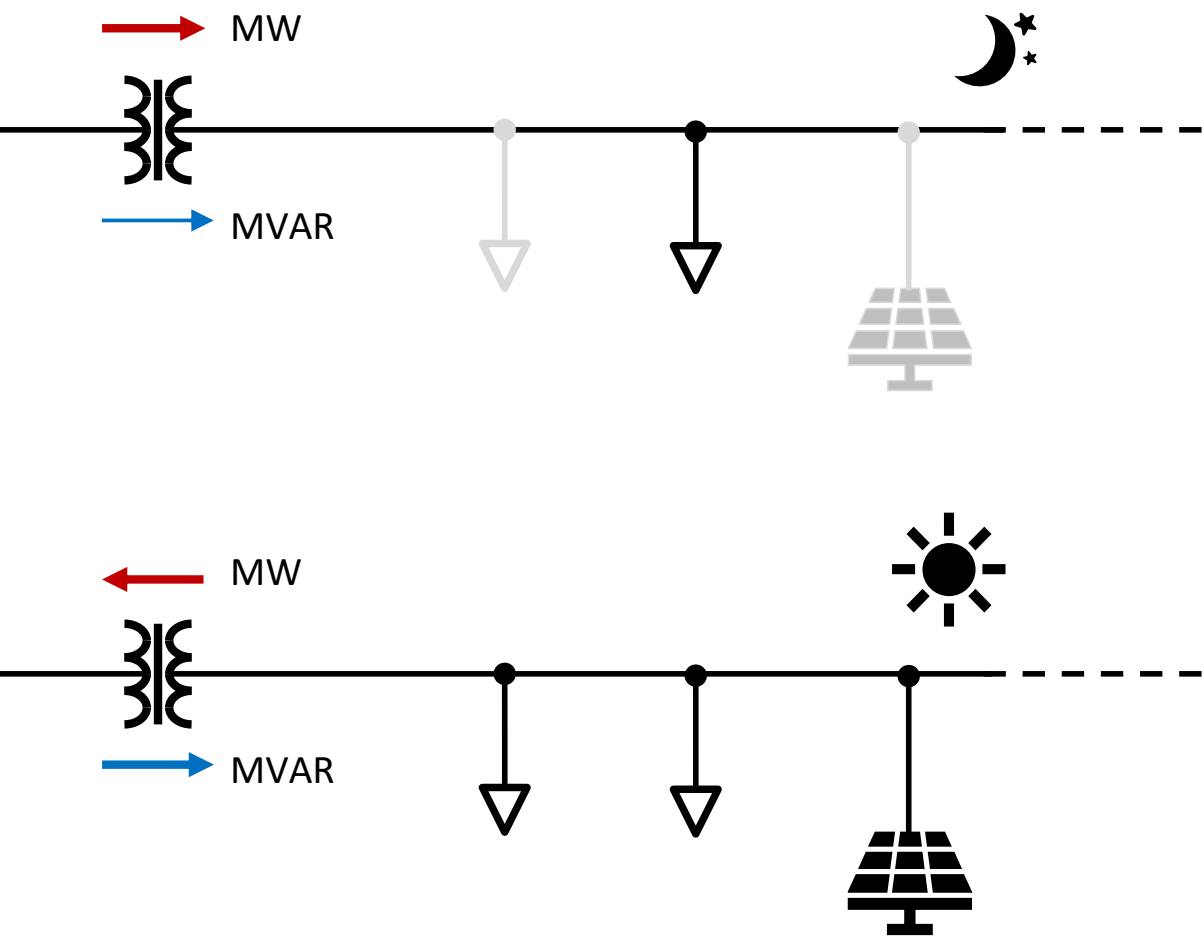
▪ Transformer “SH”

- 16.8 MVA, 126.7kV/13.2kV, no LTC
- Data collected from 6/1/2021 to 5/31/2024 (hourly interval)
- Reverse power flow for 19% of the time



Lower voltage during reverse power

Daily Profiles for Transformer “SH”

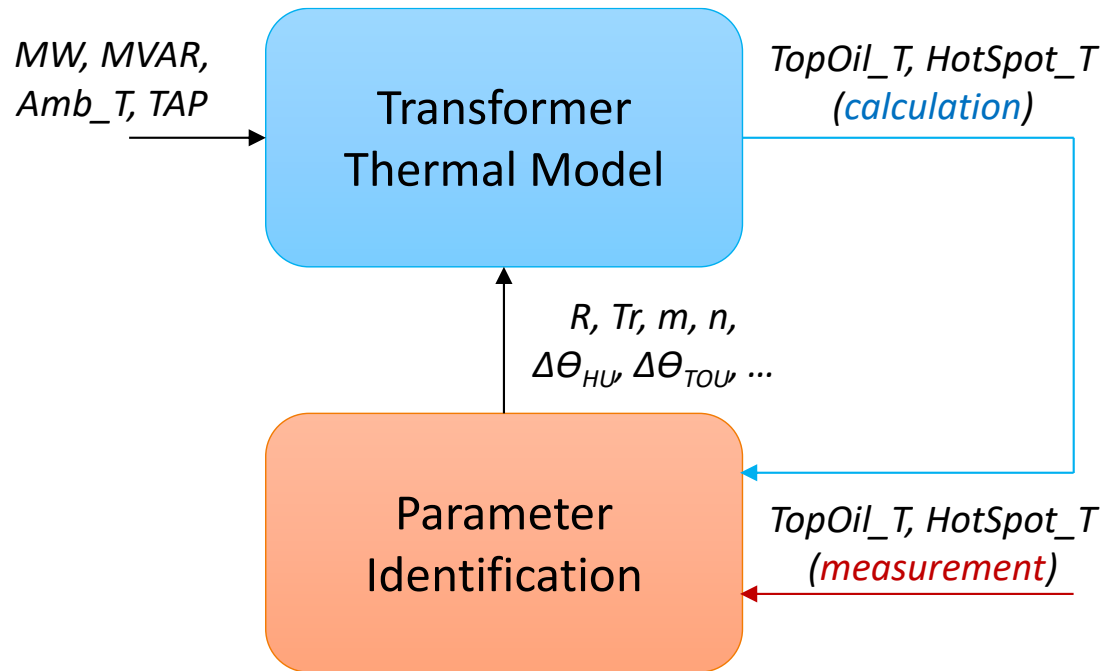


Higher MVAR load in daytime leads to lower voltage

Source: *The Effect of Reverse Power Flows on Substation Transformer Banks: Review of Industry Practices and Literature, Field Data Analysis, and Rating Impacts* - <https://www.epri.com/research/products/000000003002030664>

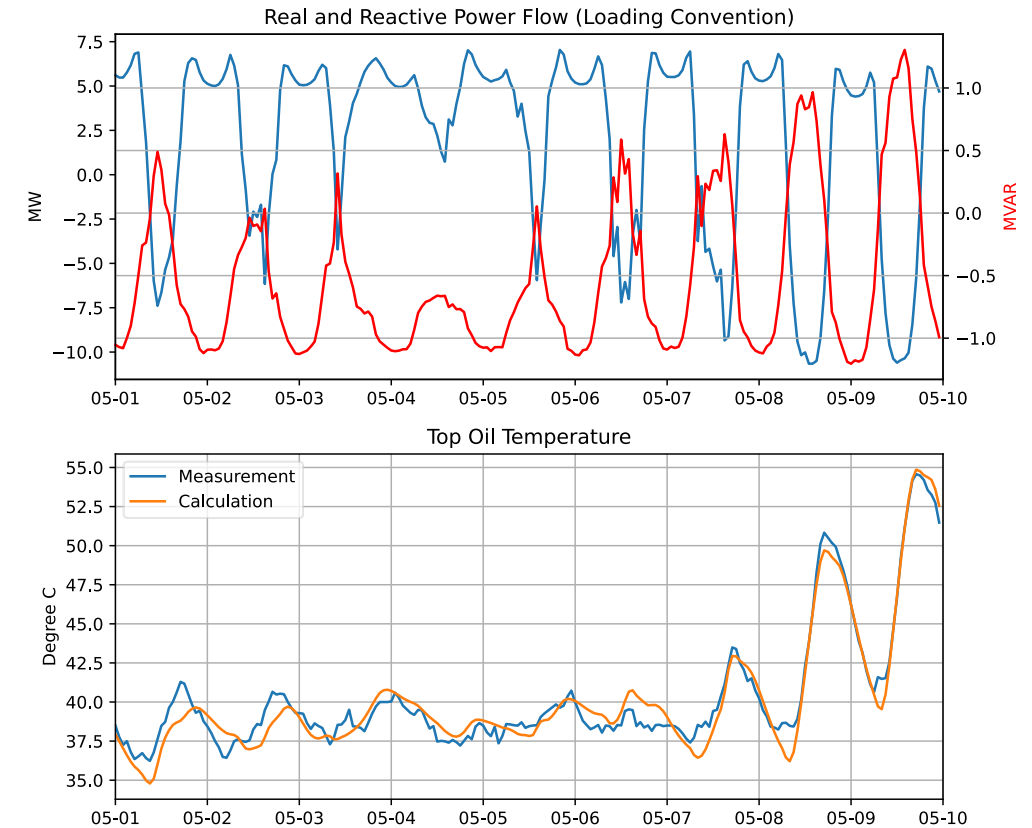
Thermal Model Simulation of Transformer “SH”

- Initialize thermal model parameters based on transformer factory test report
- Fine tune parameters to minimize errors between calculation and measurement using optimization



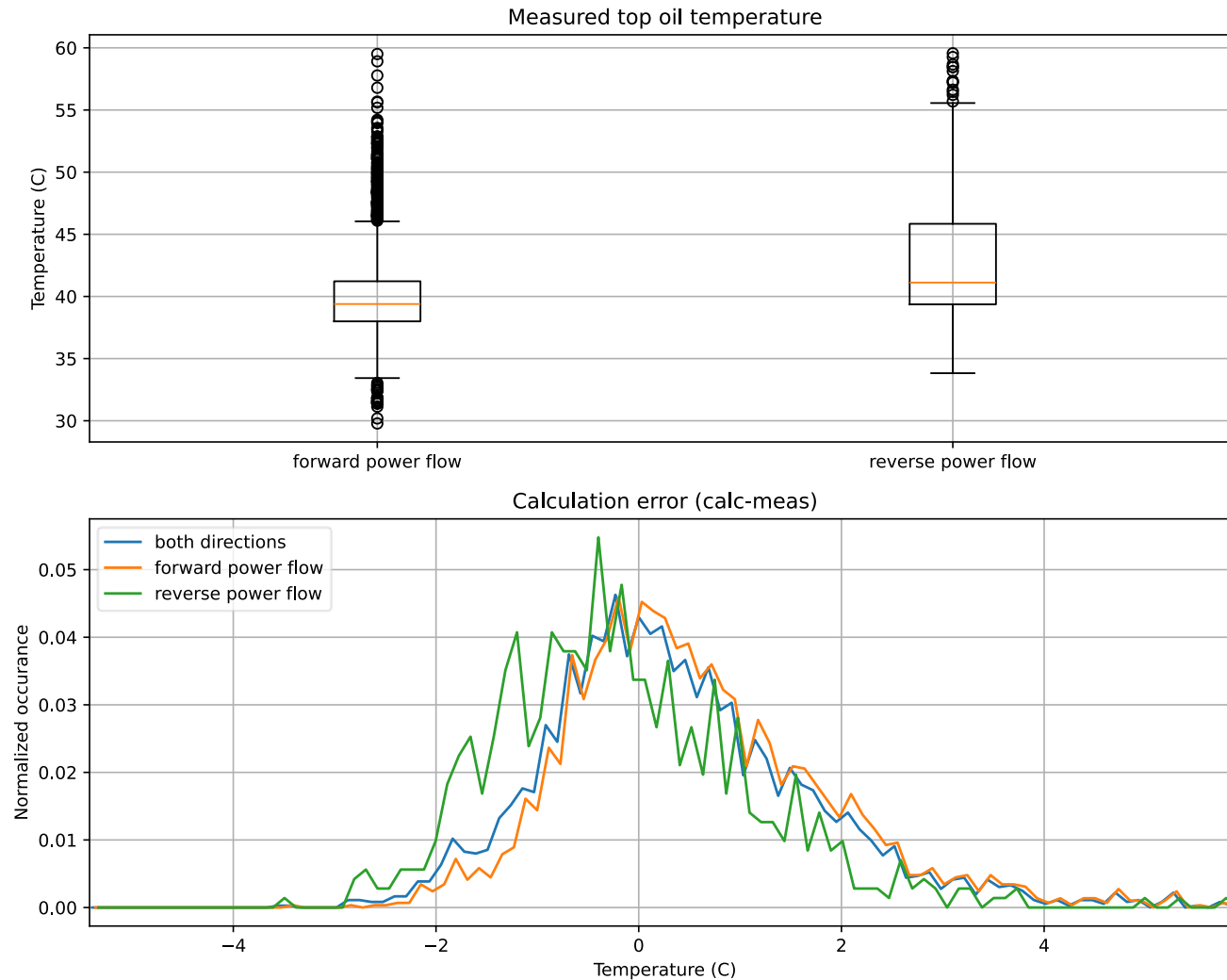
Thermal method reference: IEEE Std C57.91-2011

Time series data of two weeks in May 2023



- Calculated temperatures from the thermal model **closely match** that from the measurement **in both power flow directions**

Simulation Error per Power Flow Directions



Top Oil Temperature

- All power flow directions
 - 95% of the calculation error < 2.9°C
- Forward power flow
 - 95% of the calculation error < 2.9°C
- Reverse power flow
 - 95% of the calculation error < 3.0°C

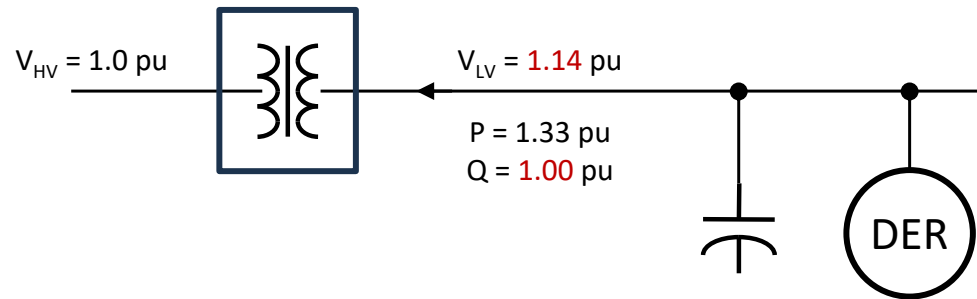
No evidence suggests invalidity of the model in reverse power

A blue-toned image featuring a hand holding a globe. The word "Backup" is written in white, bold, sans-serif font across the center of the globe. The background is a deep blue with faint, glowing star patterns and a subtle grid of lines, suggesting a digital or space theme. The hand is positioned at the bottom, with fingers gently cradling the globe.

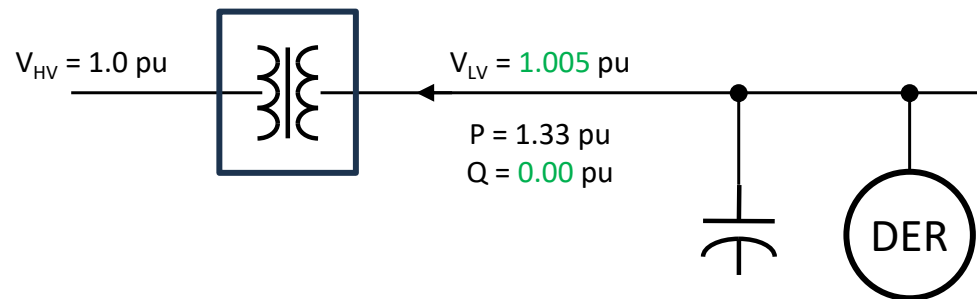
Backup

Load Flow Showing the Cause of High Voltage

Case 1:



Case 2:



Case 1:

- Leakage impedance $Z = 15\%$, $X/R = 8$
- 133% reverse power from high DER penetration
- PF = 0.8 capacitive (producing vars)
 - 10MVar for a 10MVA substation transformer
- No LTC, LV side voltage $V_{LV} = 1.14$ p.u.

Case 2:

- Same reverse power, but unity power factor
- LV side voltage $V_{LV} = 1.005$ p.u.

Reverse Active Power is NOT the Reason for Over-Excitation

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