

IEEE Transformer Committee Spring 2021 Meeting – Tutorial “Reverse Power Flow Impact on Transformers”

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Overview Presentation – WG C57.133

Oct 29, 2024 - Ed teNyenhuis Hitachi Energy

Agenda

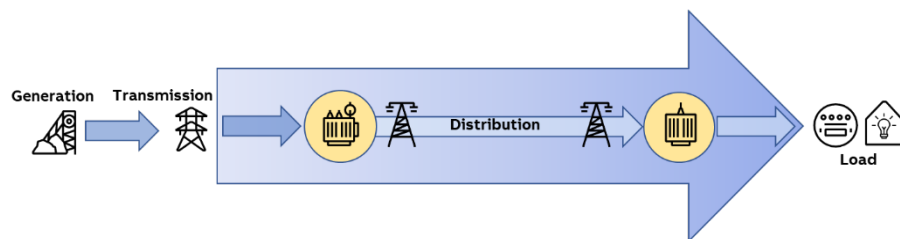
- Introduction to Reverse Power Flow
- Changes from a utility perspective
- Impact on transformers
- Impact on load tap changers (LTCs)
- Transformer Case study
- Conclusions

Impact of Reverse Power Flow on Transformers

Traditional vs Modern Electrical Power Grid

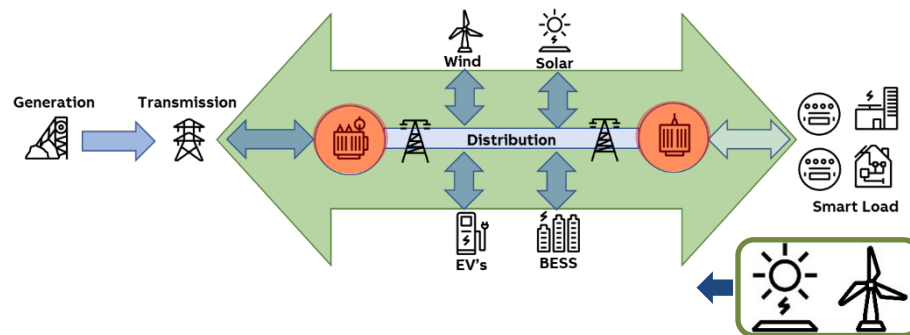
Traditional Grid

Conventional unidirectional Power flow



Modern Grid

Modern Grid with Distributed Energy Resources (DER)



DER Injecting power to the grid (Reverse Power)

Insufficient energy storage capacity at the DER generating nodes leads to bi-directional power flow

Utility Perspective

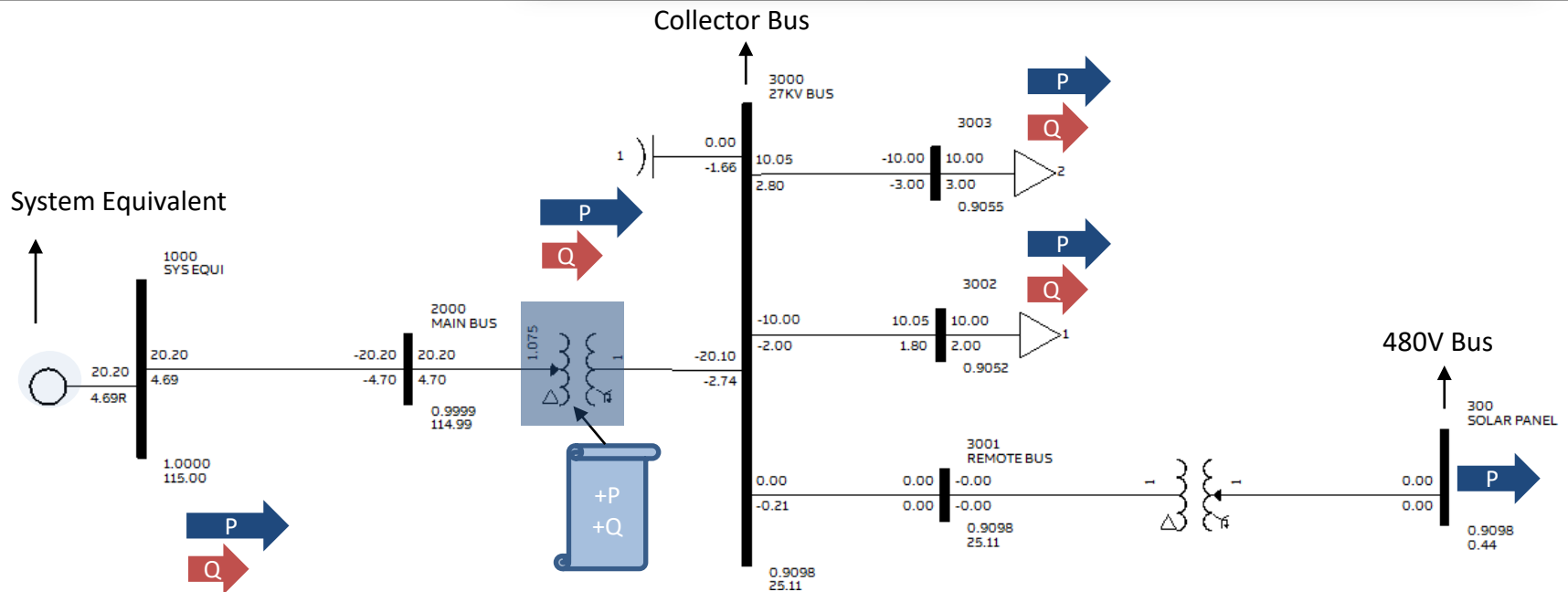
- Unique RPF transformer loading guidelines required?
- Short-term RPF transformer loading limits?
- Long-term RPF impact on transformer insulation life?
- How to develop approx RPF load profiles including peak load duration for residential, small / large industrial customers?
- When does installation of distributed generation require an upgrade to transformer capacity size?
- Does end user transformer specification require specific RPF application details?
- Transformer RPF application details required by the manufacturer?
- Will RPF specification requirements affect transformer design and installation requirements (poles, foundations, cost, etc.)?

Typical Transmission/Distribution Substation

Equivalent Representation

Mode #1

Normal situation of + positive Active and Reactive power flow through transformers

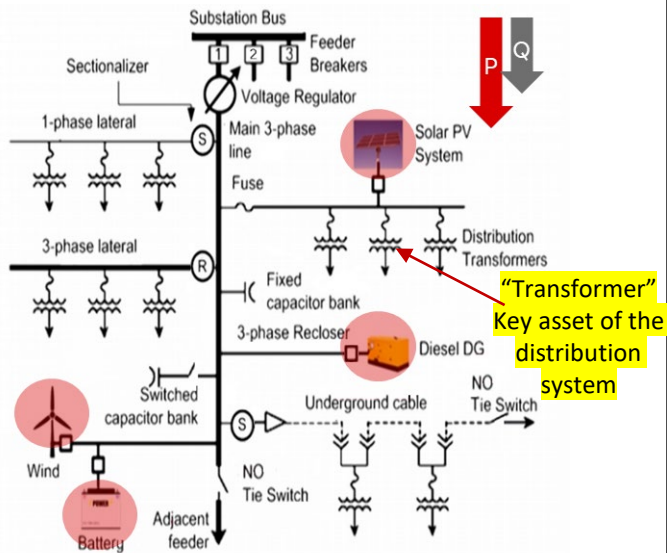


Impact of Reverse Power Flow on Transformer

Active and Reactive power can be in any of the 4 quadrants depending on the DER scenario

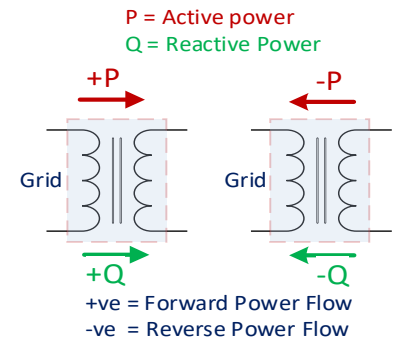
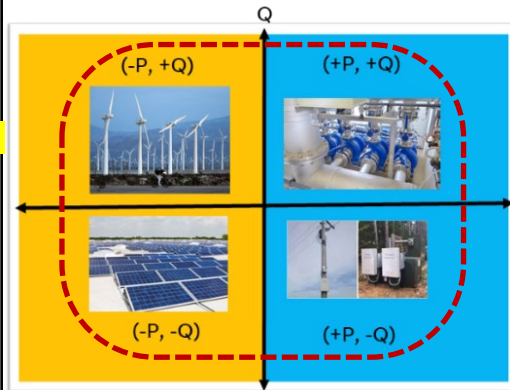
Typical Transmission/Distribution Substation

Typical T&D Substation



Four Power-flow Scenarios

- Nominal load w/ Inductive kVAR Demand (Motors)
- Load w/ Capacitive kVAR (Voltage Regulators)
- DER w/ Inductive kVAR demand (DFIG Wind)
- DER w/ Capacitive kVAR (Solar + Cap Banks)



Active/Reactive Power-flow

- +P, UPF, Lead ($-Q$) and Lag ($+Q$)
- -P, UPF, Lead ($-Q$) and Lag ($+Q$)

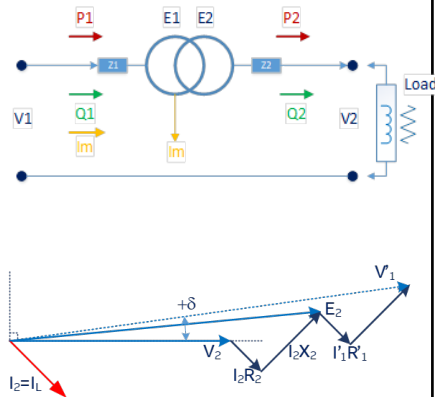
Impact of Reverse Power Flow on Transformer

Transformer Operation Under Reverse Power-flow

V_1 = Terminal Voltage at Winding 1 (Grid)
 V_2 = Terminal Voltage at Winding 2 (Load)
 $E_1 = E_2 = E_m$ = Magnetizing Voltage

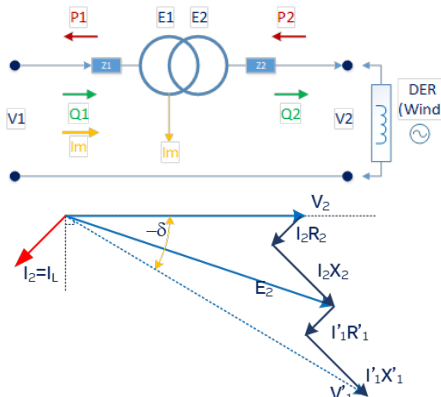
Quadrant-I

- +P, +Q, $V_1 > E_2 > V_2$, $\delta > 0$
- $E_2 = E_{21}$ is the design point



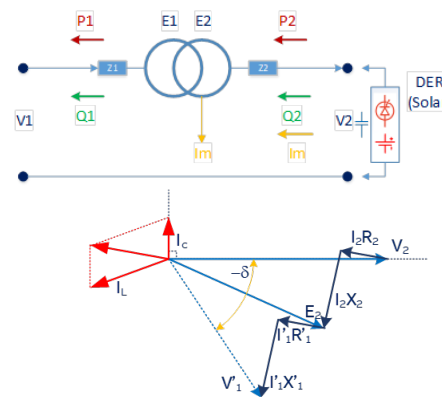
Quadrant-II

- -P, +Q, $V_1 > E_2 > V_2$, $\delta < 0$
- $E_2 > E_{21}$



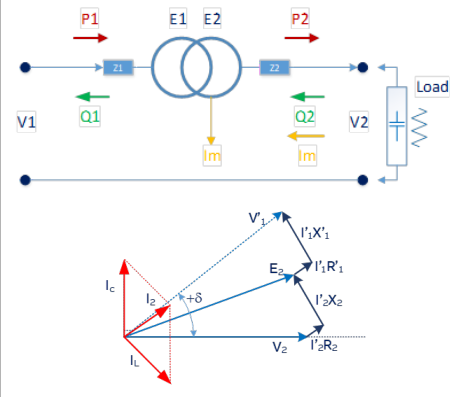
Quadrant-III

- -P, -Q, $V_1 < E_2 < V_2$, $\delta < 0$
- $E_2 > E_{21}$



Quadrant-IV

- +P, -Q, $V_1 < E_2 < V_2$, $\delta > 0$
- $E_2 < E_{21}$



Under this investigation Grid voltage V_1 is assumed to be constant and E_{21} is the design point

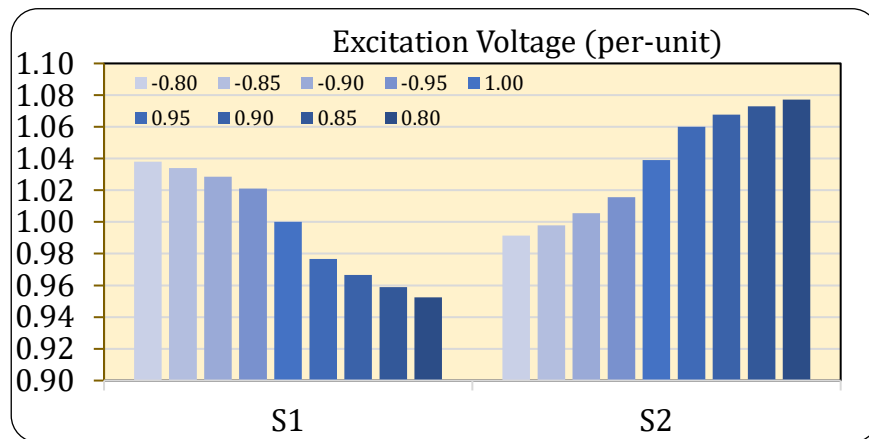
Large impact on magnetizing voltage under different active & reactive power flow

Impact of Renewables on the Substation Transformer

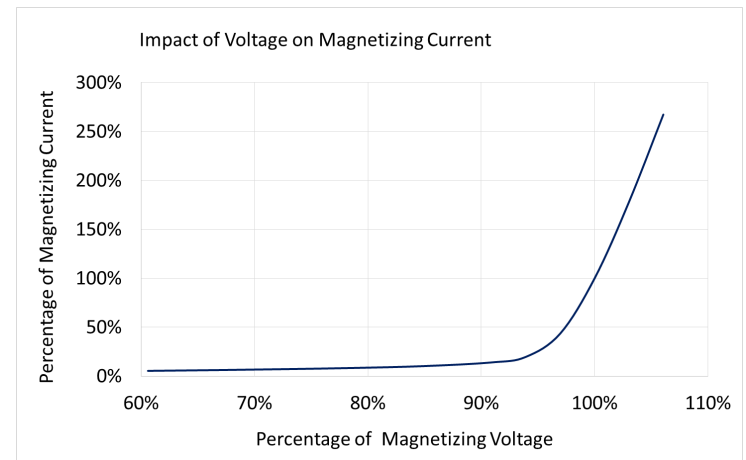
Excitation voltage 'E' is variable depending on power flow scenarios

Effect of active and reactive power flow on excitation voltage

Percentage change in excitation voltage compared to the rated



Effect of active and reactive power flow on magnetizing current



- Percentage change in magnetizing current compared to the rated

Usually, Magnetizing current is very low for transformers, two-fold increase will not cause issue

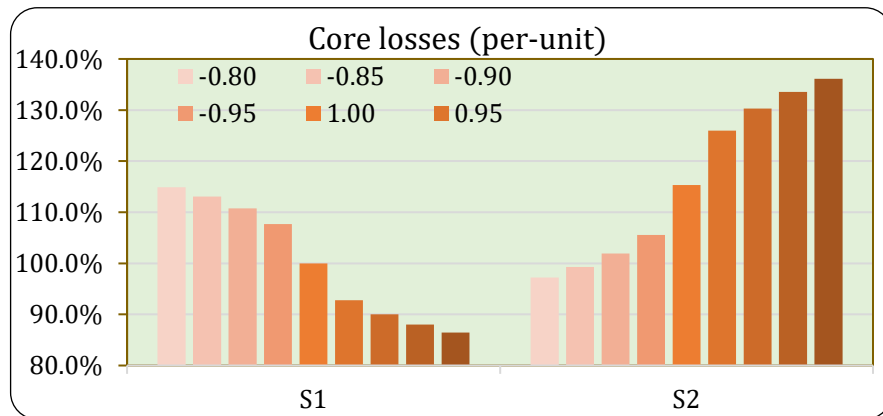
Excitation voltage variation as a function of active / reactive power flow and power factor

Impact of Renewables on the Substation Transformer

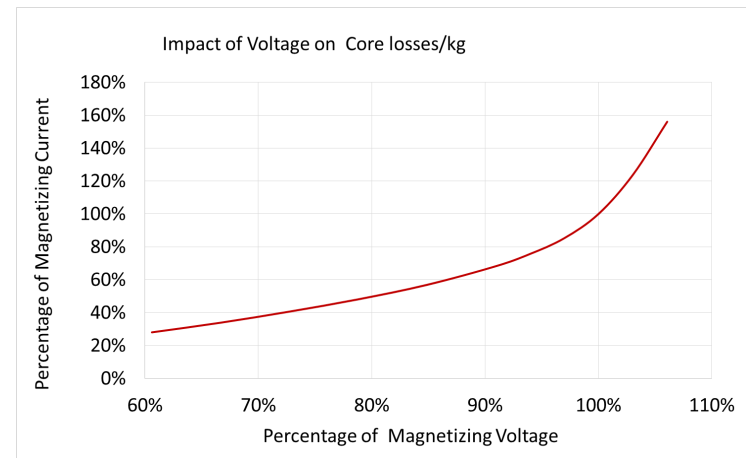
Excitation voltage 'E' is variable depending on power flow scenarios

Effect of active and reactive power flow on core losses

Percentage change in excitation voltage compared to the rated



Effect of active and reactive power flow on core losses



- Percentage change in core losses compared to the rated

Small increase in excitation voltage significantly increases the core losses, which impact life of the transformer

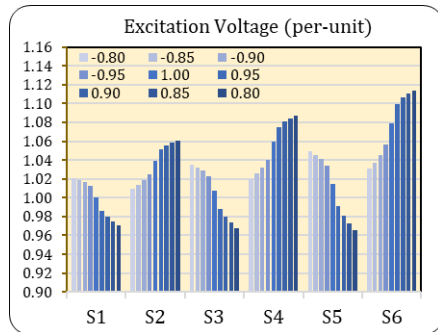
Impact of Reverse Power Flow on Transformer

Four (4) Cases – Short Circuit Impedance [9.0% & 15.0%] and Core Flux Density [1.65 & 1.72 T]

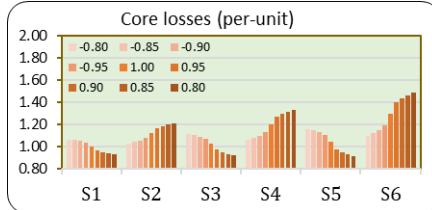
Six (6) Load Scenarios: S1 (100% F), S2 (100% R), S3 (133% F), S4 (100% R), S5 (166% F), S6 (166% R)

Short circuit impedance (Z_{sc}) = 9.0%

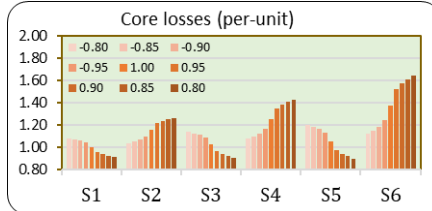
- Range of excitation voltage is from 0.96 to 1.12 pu



$B_m = 1.65$ T

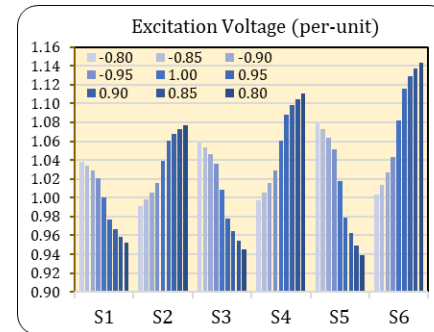


$B_m = 1.72$ T

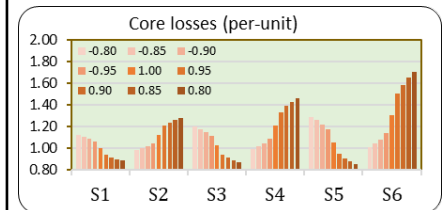


Short circuit impedance (Z_{sc}) = 15.0%

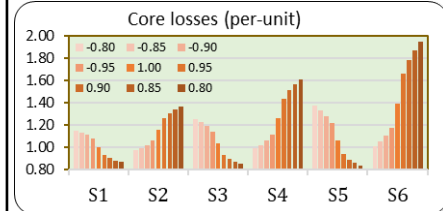
- Range of excitation voltage is from 0.94 to 1.14 pu



$B_m = 1.65$ T



$B_m = 1.72$ T



This small increase in excitation voltage significantly changes the excitation current and magnetic core losses.

Impact of Reverse Power Flow on Transformer

Summary:

Today's challenge is that the levels of increased (load or line-side) voltage and voltage harmonics caused by reverse power flow have been mostly not communicated, or not considered in transformer specifications.

Impacts

- The phenomena of reverse power flow impact the performance of the interconnect transformers.
- The operating power factor has also significant impact on the transformer losses.
- The amount of impact on transformer life depends on design of the transformer and operating conditions.
- If the reverse power flow is not restricted, then interconnect transformer loses its life.

Solutions

- The restriction on power factor of reverse power flow can maintain the life of transformer.
- To operate transformer without loss of life, and unrestricted/unconditional operations, a customized transformers are developed based on system analysis and study.
- Transformer manufactures have experience in design to resist these types of stress when the system characteristics are known.
- As an intermediate step to address already installed units, digital technologies to monitor for load flow, total harmonic distortion (THD) and primary/secondary voltage at the transformer can be installed in order to get better predictability of potential failures and increased aging characteristics.

- Evolution of the Grid Structures (Changes from 2010 to 2025)
 - Change of Load Balance and Power Flow cause an **increased requirement of reactive power** and **dynamic voltage fluctuations**.
 - Increased reactive power requirements on the distribution level will cause **additional stress to the grid assets**.
 - A change in consumption will cause a higher effect to the stability of the grid frequency due to **missing compensation by synchronous generators**.
 - High level of renewable generation is **moving the operating point for conventional synchronous generation units into economically unfavorable regions** with limited counteractions based on conventional infrastructure.
 - Conventional infrastructure at the transmission level will cause **service interruptions** and **frequent maintenance schedules** due to dynamic fluctuations and inadequate reactive power equipments.

What are the effects on LTCs ?

■ Effects on LTCs

– Increased number of operations:

⇒ faster ageing; may this result in shorter maintenance intervals ?

Fact: Typical LTC maintenance intervals:

- ◆ 50'000 – 80'000 operations, or after 5 – 7 years (non-vacuum type LTCs)
- ◆ 300'000 – 600'000 operations (vacuum type LTCs; no time-based maintenance)

Example: LTCs in network service typically perform 1000 – 5000 op./year

⇒ maintenance intervals are 10 – 600 years

⇒ time-based maintenance or no maintenance applies

⇒ **In case the number of operations/year is doubled, maintenance intervals will remain the same (no impact).**

⇒ **More than a doubled number of operations/year can cause increased maintenance.**

– Decreased $\cos \varphi$ (power factor, $\angle U, I$):

⇒ increased duration of switching arcs; will this result in higher contact wear ?

Fact: All LTCs have been designed to break pure capacitive or reactive currents.

⇒ **Contact lifetime is not reduced below the nominal value (no impact).**

– Increased voltage amplitude for regulation:

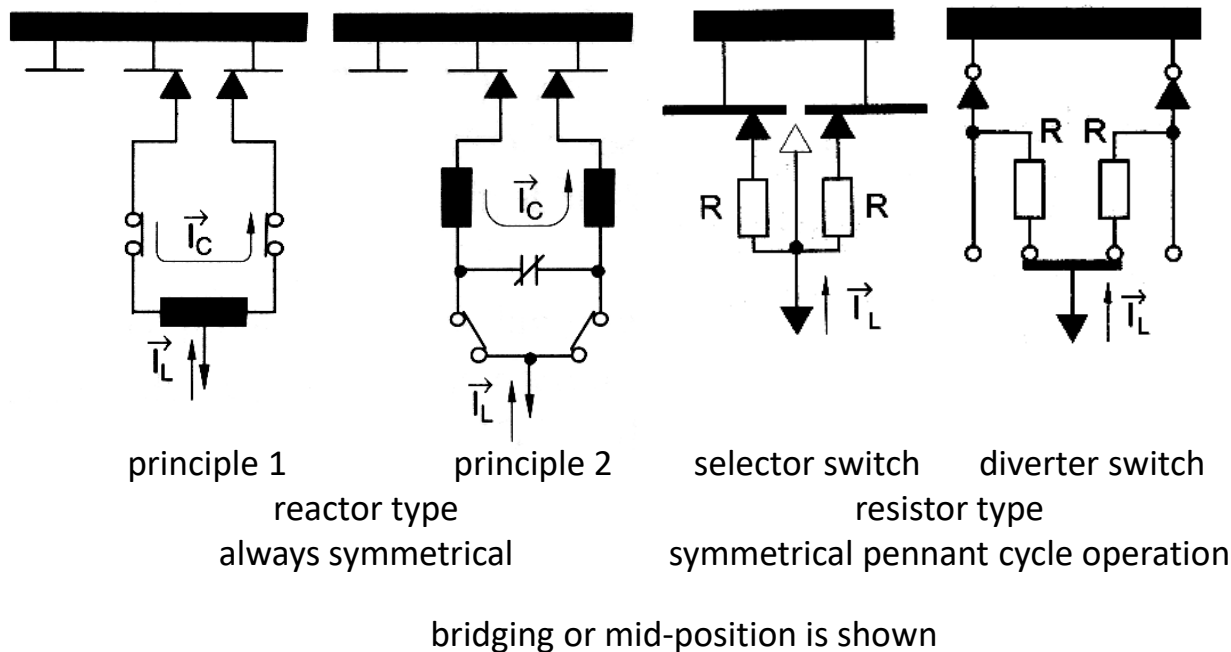
⇒ full regulating range will be utilized.

⇒ **Contact wear on fixed contacts is reduced (longer life/no impact).**

⇒ **New transformer designs might require longer regulating windings (extended regulating range, more taps).**

■ LTCs and Reverse Power Flow

- Almost all LTCs can handle reverse power flow:
 - ♦ Designed to switch load current I_L *plus* circulating current I_C
 - ♦ Tested with worst case power factor conditions
($\cos \varphi = 1$ for resistive type LTCs, $\cos \varphi = 0$ for reactive type LTCs)



■ LTCs and Reverse Power Flow

- One old LTC design for uni-directional power flow (age >40 years):
 - ♦ selector switch, resistor type, 1 resistor
 - ♦ “asymmetrical pennant cycle operation”
 - ♦ typically applied in transformers 33/11kV, 10-40MVA
 - ♦ Spread: UK, Australia
 - ♦ Manufacturers: e.g. Fuller, Ferranti



Fuller LTC



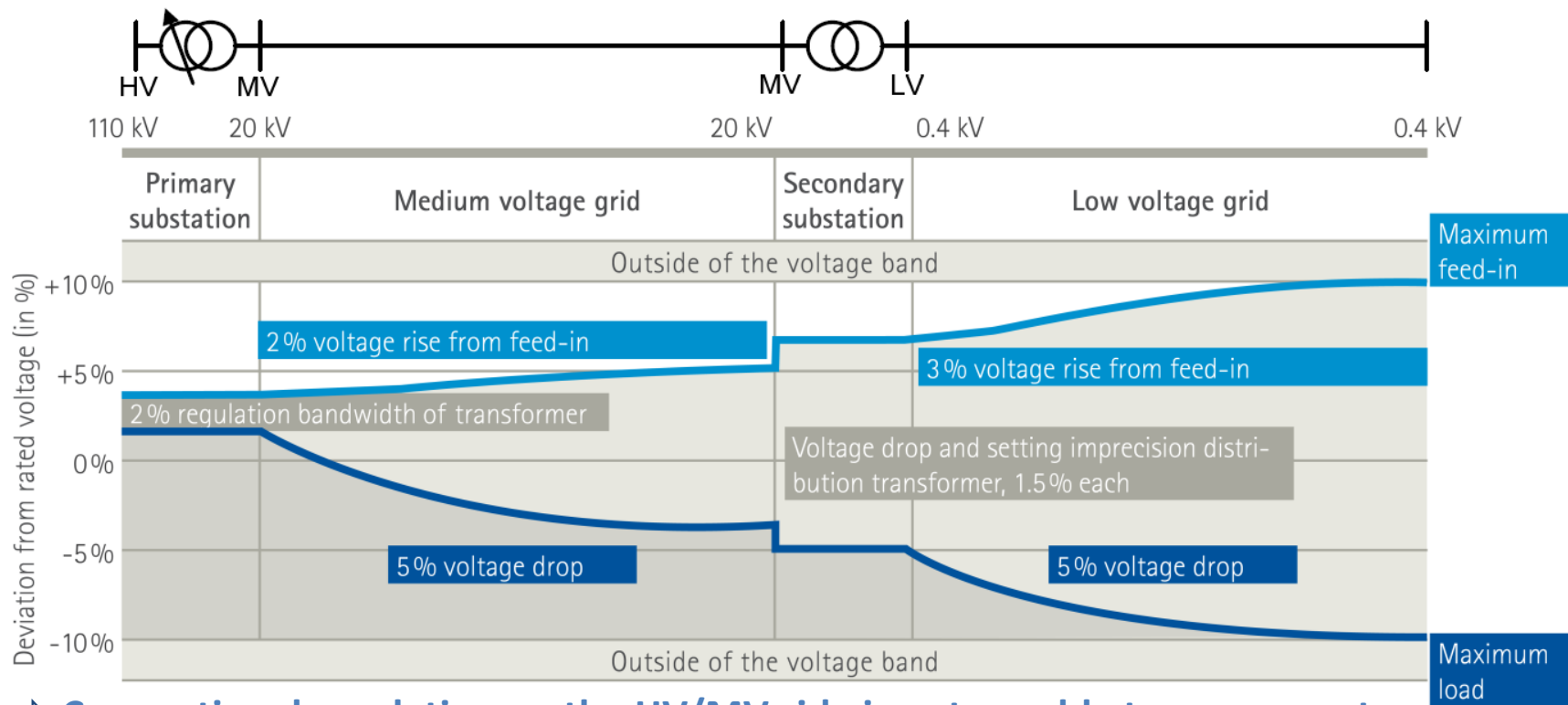
Ferranti LTC

These LTCs are NOT suitable for reverse power flow !

pictures by courtesy **BRUSH**

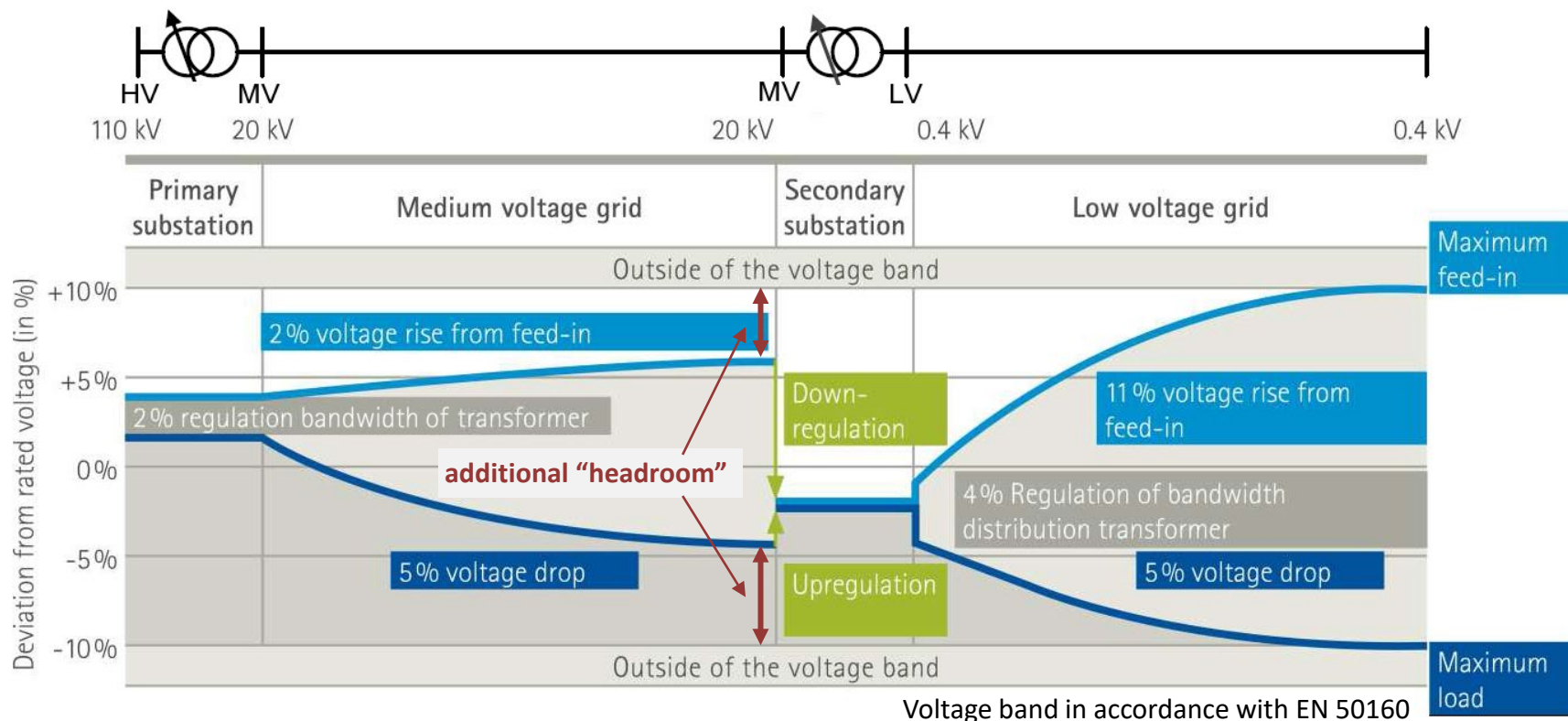
■ How can the challenges, caused by the feed-in from Distributed Energy Resources, be met ?

— Typical grid topology:



- ⇒ Conventional regulation on the HV/MV side is not capable to compensate for high voltage fluctuations in the low voltage grid.
- ⇒ Power which can be fed into the low voltage grid is limited.
- ⇒ Full regulating range of HV/MV transformer cannot be utilized.

- By using a Voltage Regulating Distribution Transformer (VRDT)
 - Benefits have been identified for different application scenarios.



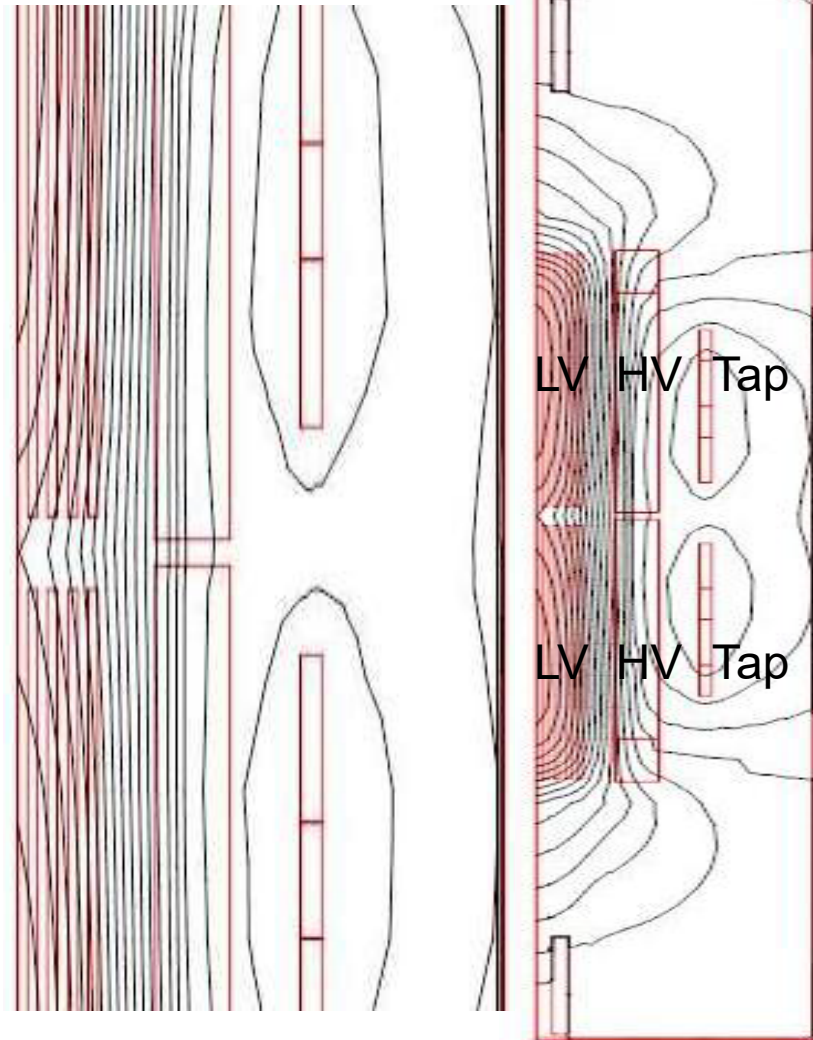
- ⇒ By applying a VRDT, the LV and MV grids are decoupled.
- ⇒ Voltage band problems in LV and MV levels are eliminated.
- ⇒ Reactive power management / grid topology can be optimized.
- ⇒ Increased power feed on LV side is enabled.

Case Study - Reverse Power Flow

- 125 MVA Transformer with OLTC in HV
- 215.50 / 28 / 28kV (dual LV)
- LV windings are axial halves
- HV are 2 halves in parallel
- Designed for step down operation (HV to 2 LV's)
- Transformer now requested to operate for step up and LV to LV due to new 28kV generation

Normal Step Down

- Leakage Flux (Real)
- Amp – Turns are balanced
- Check on winding, lead, core, tank, clamp, tie plate
- Temperatures all within limits



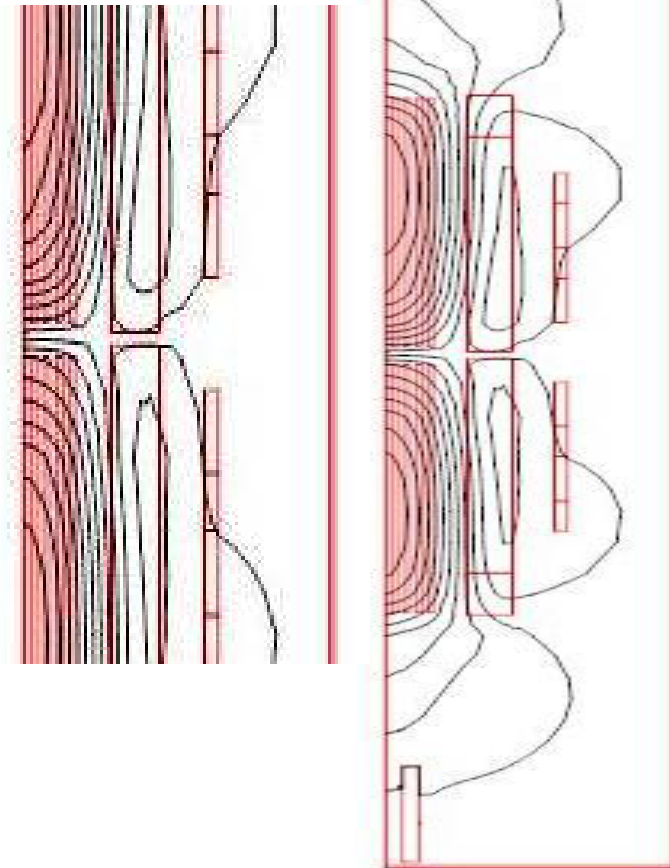
Core Tie Plates

- Tie plates are used to connect the top and bottom clamps and hold the limbs together (example shown)
- Heating is dependent on material, width and amount of leakage flux



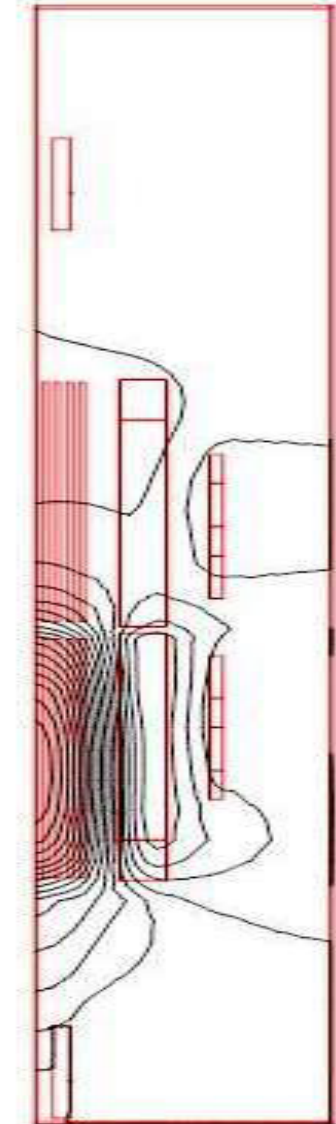
LV to LV

- Eddy losses greater due to concentration of flux lines between LV windings
- Outer core packets and tie plates very high temperature due to much higher leakage flux
- Loading must be reduced to 20 MVA (!!) for safe operation with all cooling in operation



HV to 1 LV

- Leakage flux (real)
- Not as severe as LV to LV
- Outer core packets and tie plates still have very high temperature



Conclusions of Reverse Power Flow (1)

- Will have a large impact for utilities.
- Can impact performance of interconnection transformers.
- Transformer core and harmonic losses can be 15% higher.
- Reverse active and reactive power flow condition (Q3) has maximum core losses for any load conditions.
- If reverse power flow is not restricted, then interconnection transformers can have life reduced by 25%.
- Restriction on power factor of reverse power flow can maintain life of the transformer.

Conclusions of Reverse Power Flow (2)

- Impact on transformer life depends on design of the transformer and operating conditions.
- System studies that account for over-voltage and increased harmonics can be used to improve transformer specifications and design.
- Most OLTC models are capable to handle reverse power flow but may need more maintenance due to increased switching frequency
- Transformer design review may be necessary to confirm suitability for reverse power flow on existing assets.
- Voltage Regulated Distribution Transformers are an effective measure to minimize reverse power flow and to retrieve grid stability