Distributed Energy Resources (DERs): Impact of Reverse Power Flow on Transformer

P. UPADHYAY* - ABB US Power Grid Research
J. KERN - ABB Global Product Manager
V. VADLAMANI - ABB Power Consulting
USA

Summary

The analysis of this paper will answer two important questions, (i) does reverse power flow impact the performance of existing transformers in the grid? and (ii) does It make sense to replace interface transformer using a customised design to minimize restrictions on reverse power flow? The answer to both questions is "YES", and the reasons and operating limits are presented in this paper. The global energy demand is predicted to increase at about 5% compound annual growth rate (CAGR). The power industry demands the least life cycle cost (LLCC) with respect to lower capital cost and running cost. The wind (539 GW) and solar (403 GW) markets are the two major variable renewable energy (VRE) sources sharing the majority of new renewable generating capacity globally. Due to the highly unpredictable nature of such VRE sources, in many circumstances, the instantaneous power demand and supply do not always match, and insufficient energy storage capacity at the DER generating nodes leads to reverse power flow towards the grid. Having large capital investments, renewable developers would like to see maximum energy production achieved to minimize payback periods. However, under lower demand periods, utilities and grid operators reject the renewable energy fed back to the grid. The interconnection transformers observe loss of life due to the impact of the reverse power flow. Transformers are the back-bone of the grid, and the expected life of substation and grid interface transformers are very high. Increased loss and thermal cycling reduce transformer life. Small increase in the excitation voltage above the limits leads to significant magnetizing current increase and harmonics. The core losses impact the temperature-rise and the life of the transformer. Comparing the results of various operating conditions, reverse active and reactive power flow is the worst. There should be restrictions on power flow without the loss of transformer life or else transformer needs to be replaced with the customized designs to assure the standard life.

1. Introduction

The global energy demand is predicted to increase at about 5% compound annual growth rate (CAGR). The power industry demands the least life cycle cost (LLCC) with respect to lower capital cost and running cost. Most developed nations have energy sustainability programs using renewable energy generation and energy conservation through smart operating systems, which provide the optimum energy management scenarios to maintain LLCC. Renewable energy is expanding in the power sector, with 181 GW newly installed in 2018 [1]. Due to the modern fast EV charging stations, EV battery systems, distributed energy generation, and energy storage; the penetration of distributed energy resources (DERs) has grown to around 2,378 GW in 2018 to account for more than 33% of the world's total installed power generating capacity. The wind (539 GW) and solar (403 GW) markets are the two major variable renewable energy (VRE) sources. In 2018, more than 90 countries had installed at least 1 GW of generating capacity, while at least 30 countries exceeded 10 GW of capacity [1]. Eleven of the 28 EU states reached their renewable energy targets for 2020 in 2017, according to a report by the EU statistical office Eurostat [2]. 37 of the 50 states within USA have renewable energy standards for interconnecting renewable energy resources and 8 of the 50 states have voluntary Renewable Energy Portfolio Goal of at least 25% by 2035 [3]. Fourteen common

*parag.upadhyay@hitachi-powergrids.com

KEYWORDS
Renewable transformers, interconnect transformer, Reverse power flow, loss of life, four quadrant operations, core losses, distributed generations

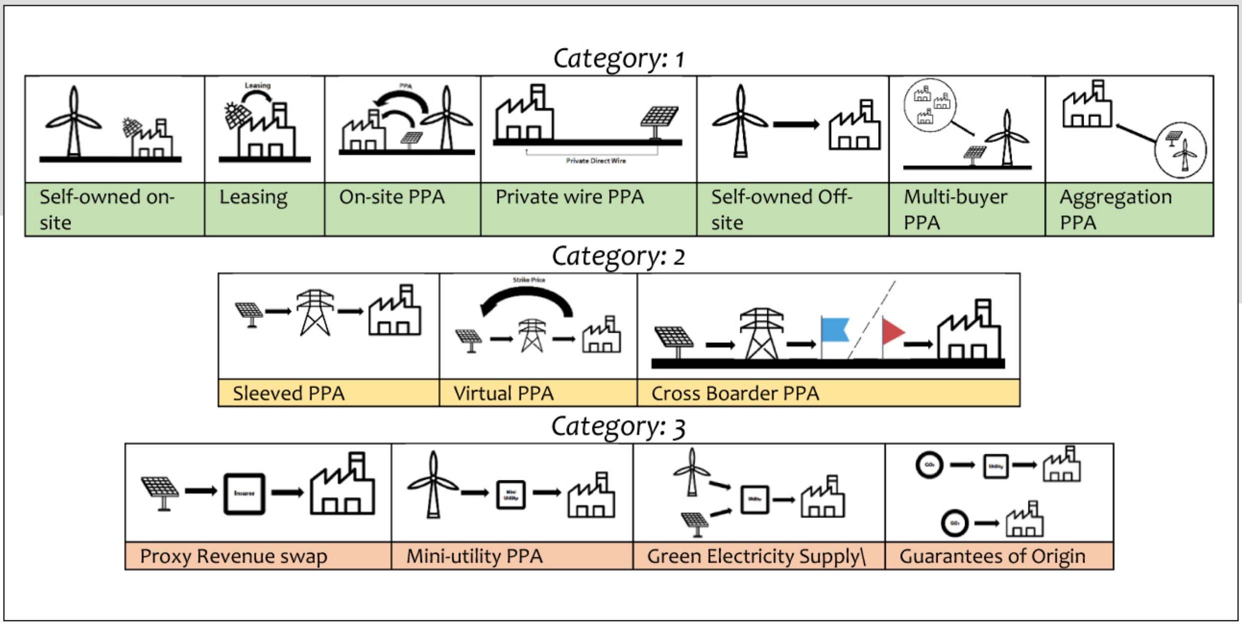


Fig 1 Transition from past to future on power flow condition at the interconnect transformers

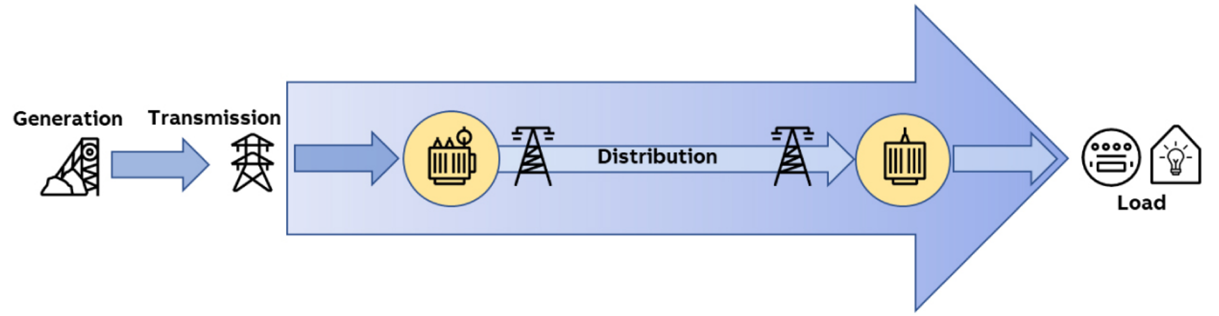
models have been identified (Re-Source: A European platform for corporate renewable energy sourcing) in Europe considering various power purchase agreements (PPA).[4]

PPA is an important contract that governs the sale and purchase of power which provides reliable long-term clarity on roles, responsibilities, costs, revenues as well as probability and significance of associated risks for stakeholders. In a complex Off-site PPA models, the off-taker is responsible for moving the energy away from the delivery point (DER) to its load, typically done through 3rd-party service providers (Mostly Utilities). Due to unfamiliarity of their potential accounting impacts on the asset health managements, the impact of reverse power flow on transformer is inevitable as described in this paper. Out of 14 PPAs, utilities provide the energy transport platform for categories 2 and 3 therefore the bidirectional power flow is considered in this paper.

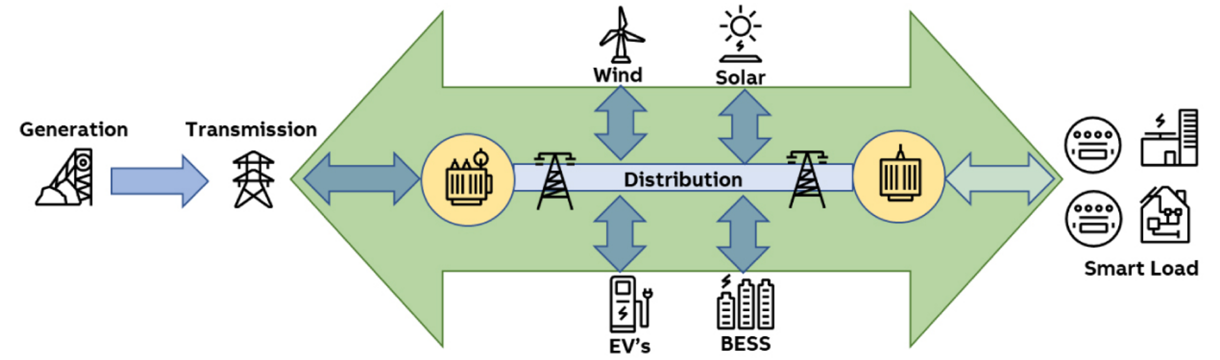
2. Integration of renewables to the system

Traditional power system network was designed for accepting power flow from generation to load via transmission and distribution networks. With the shift in the global demand for energy, the traditional power system as we know it is shifting its dynamics to accommodate the renewable energy resources. The penetration of the Distributed Energy Resources (DERs) on distribution and transmission networks is disrupting the traditional power flow to become bidirectional as shown in fig.2. A reversal of the traditional power flow from distribution to transmission system by too much DER penetration is referred as 'reverse power' flow in this paper and the interconnecting transformers are of special interest. Due to the highly unpredictable nature of such VRE sources, in many circumstances, the instantaneous power demand and supply do not always match, and insufficient energy storage capacity at the DER generating nodes leads to reverse power flow towards the grid. The challenges associated with integrating high shares of VRE – and the mix of solutions selected – vary from place to place and depend on the flexibility of existing energy systems. Effective integration of VRE calls for holistic approaches to infrastructure planning, systems operations techniques, and market and rate regulations. The wide range of generation capacities and the unpredictable amount of energy generation limits the decision making for utilities and system operators. Having large capital investments, renewable developers would like to see maximum energy production achieved to minimize payback periods. However, under lower demand periods, utilities and grid operators reject the renewable energy fed back to the grid.

The integration of the highly penetrated renewable into the energy systems also require an asset management study. The operation of power system components is affected by such integrations therefore the modification of PPAs, policies, standards, and market and regulatory frameworks to effectively harness the benefits that can be derived from renewables, while ensuring system reliability and security of supply. Policy makers and regulators in some jurisdictions are taking a leading role in attempting to address the need for increased flexibility in the grid. Integration policies require a wide variety of technical concepts, ranging from fast frequency response and synthetic inertia to enabling grid service provision from demand-side management and distributed energy resources. The physical PPA utilized for the renewable energy delivery to the users, and presently the 90% rule is applied to limit the reverse power flow condition as surmountable solution.



(a) Past-to-present power transmission system transformation



(b) Present-to-future power transmission system transformation

Fig 2 Transition from past to future on power flow condition at the interconnect transformers

3. Transformer operation: four quadrants

The energy transfer through interconnect transformer is represented as two-port network in which there are two impedances; short circuit and magnetizing as shown in fig. 3. The input port is connected to the grid and output port is connected to the load/DER generation. The primary and secondary short circuit impedance are represented as [5];

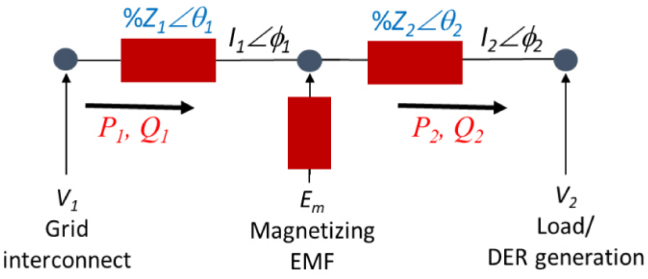


Fig. 3 Power flow representation through Transformer

$$Z\angle\theta = Z_1\angle\theta_1 + Z_2\angle\theta_2 = R_1 + jX_1 + R_2 + jX_2$$

$$\text{and, } X = X_1 + X_2$$

Also, magnetizing branch is connected b between Z_1 and Z_2. Considering negligible magnetizing current and resistance, the overall power flow equation is described in (1).

$$P = \frac{V_1 V_2}{X}\sin\delta \quad \text{and} \quad Q = \frac{V_1 V_2}{X}\cos\delta$$

The magnitude of max power transfer is defined by terminal voltages V_1 and V_2. Also, Difference in terminal voltages V_1 and V_2 in terms of magnitude and phase angle ρ, represents voltage drop in the transformer which is derived through short circuit impedance %Z and load currents. Consider load terminal of fig. 3, drawing current or injecting current to the grid at unity power factor (upf).

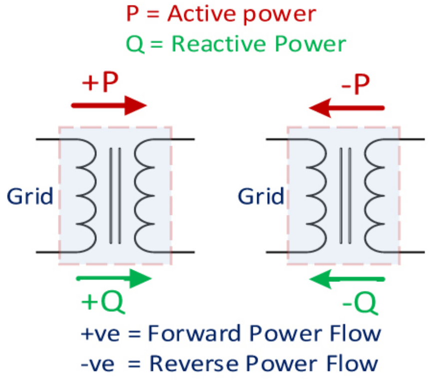
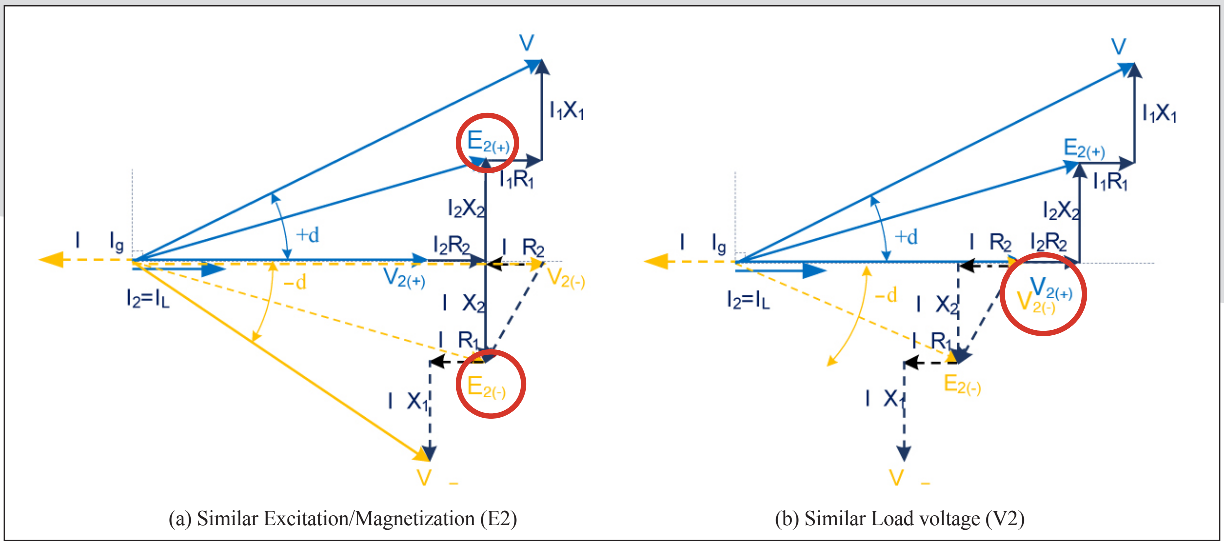


Fig 4 Typical power-flow directions

The three scenarios are represented as currents $I_2=I_L$ (as upf load), or $I_2{}'=I_g$ (as upf generation). The voltage drop across the transformer short circuit impedance creates phase displacement (ρ) between V_1 and V_2 as shown in fig.5.



(a) Similar Excitation/Magnetization (E2)

(b) Similar Load voltage (V2)

Fig 5 (a) Vector representation of transformer forward and reverse power flow at unity power factor with similar excitation/magnetization (E2) and (b) similar load voltage (V2)

For all the three cases demonstrated in fig.5 (a), (b) and (c), the positive values of ρ draws power from the grid, and negative values will inject power to the grid. The excitation voltage (E), is maintained in fig.5 (a) to maintain magnetic performance of the transformer core which necessitates the increase in injection voltage and decrease in receiving grid voltage. The second scenario fig.5(b), where the injection voltage (V_2) is maintained and both excitation and grid voltage are decreased. The third scenario of fig.5 (c) is applied to the infinite bus where, the grid voltage is constant and the injection voltage (V2) and the magnetization voltage (E) of the transformer are increased. The magnetizing flux density of the core increases in this case.

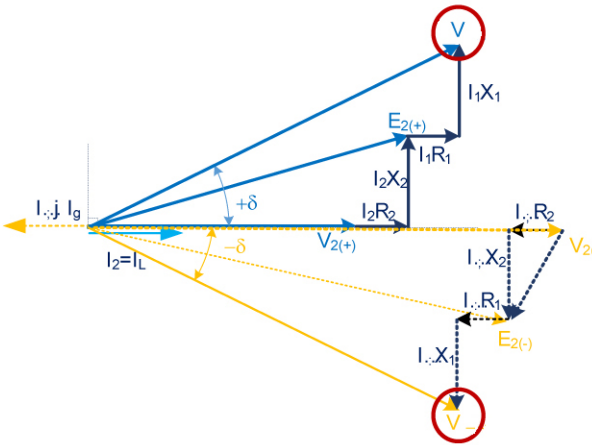


Fig 5 (c) Vector representation of transformer forward and reverse power flow at unity power factor with similar Grid voltage (V1)

Normally, the electricity utilization and generation involve the reactive power flow back and forth from grid to the load centers for power factor improvements and the voltage regulations. Therefore, in this paper describes the different power flow scenarios classified as four quadrants (Q1-Q4) as shown in fig.6.

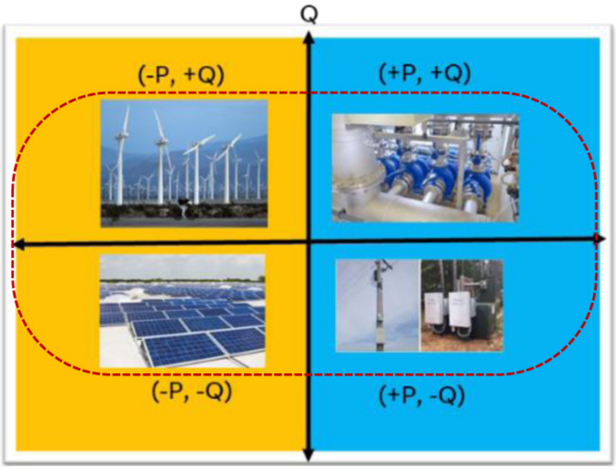
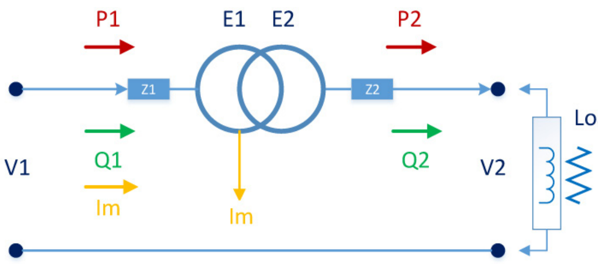
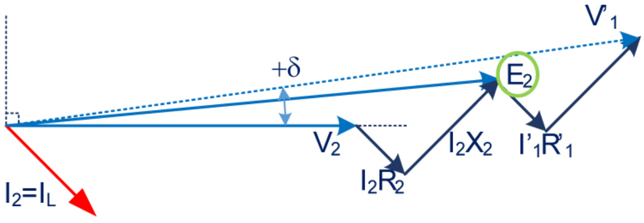


Fig 6 Fourquadrant power flow conditions

[Q1] Nominal load with Inductive kVAR demand (Motors): Motors are the example of Q1 operation of transformer. Usually motors draw lagging reactive power which is considered as [+P, +Q]. The active power flows from grid to the load with δ>0, |E|>|V2|, and the magnetizing current I_m is drawn from the grid as shown in fig.7.



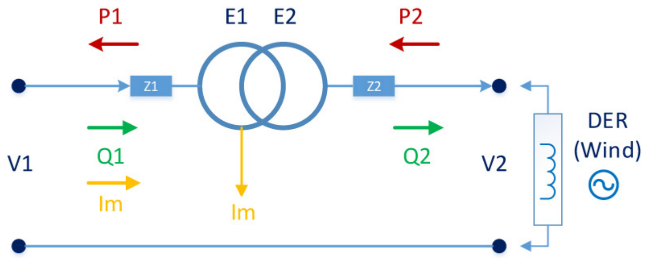
(a) Schematic diagram



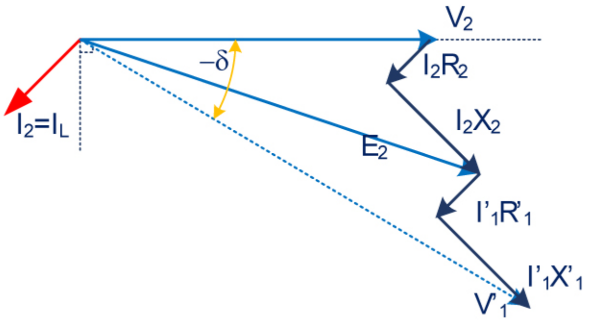
(b) Vector diagram

Fig 7 Q1: Nominal load with inductive kVAR demand (a) Schematic and (b) Vector diagram

[Q2] DER generation with Inductive kVAR demand (DFIG Wind): Induction generators coupled with the wind turbines are the induction generators which delivers active power and absorbs inductive reactive power from the grid [-P, +Q]. The active power flows from DER to the grid with $\delta<0$, $|E| > |V2|$, and the magnetizing current I_m is drawn from the grid as shown in fig.8.



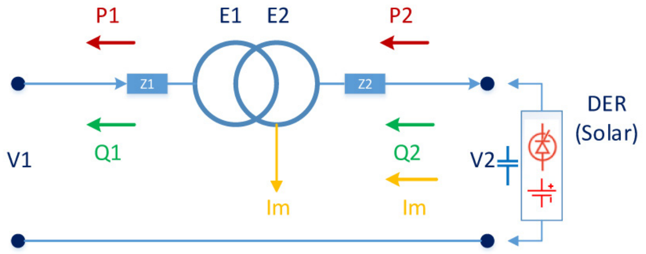
(a) Schematic diagram



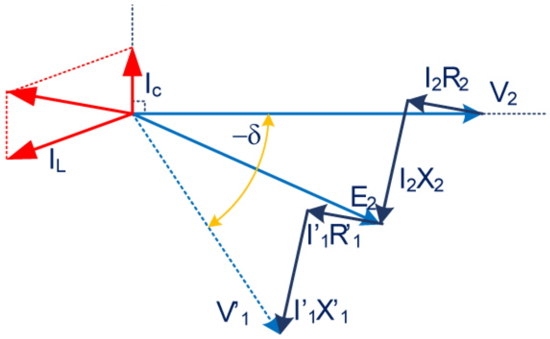
(b) Vector diagram

Fig 8 Q2: DER generation with inductive kVAR demand (DFIG Wind) (a) Schematic and (b) Vector diagram

[Q3] DER with Capacitive kVAR (Solar + Cap banks): The solar farms or the distributed solar generation includes capacitive banks for the load balancing over a time. This capacitive bank and solar panel deliver active and reactive power to the grid [-P, -Q]. The active power flows from DER to the grid with $\delta<0$, $|E| < |V2|$, and the magnetizing current I_m is supplied by DER at the load terminal as shown in fig.9.



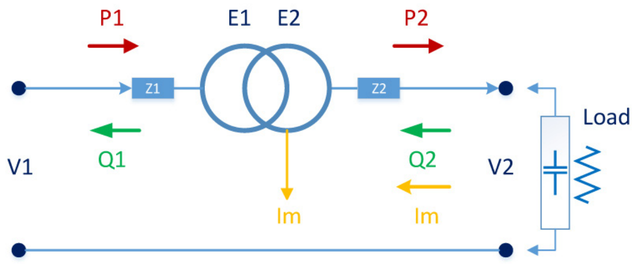
(a) Schematic diagram



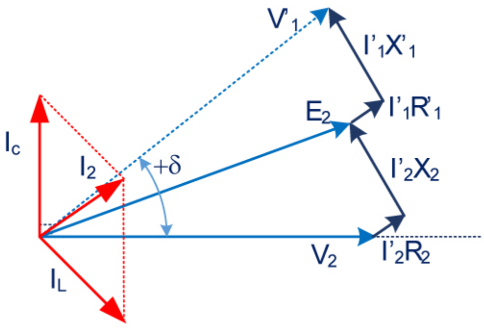
(b) Vector diagram

Fig 9 Q3: DER with capacitive kVAR demand (Solar + Cap banks) (a) Schematic and (b) Vector diagram

[Q4] Load with Capacitive kVAR (Voltage regulators): Usually capacitive banks are used to boost the load voltage and compensate line drops in the system. They are normal resistive loads and delivers reactive power to the grid [+P, -Q]. The active power flows from grid to the load with $\delta>0$, $|E| < |V2|$, and the magnetizing current is supplied by DER at the load terminal as shown in fig.10.



(a) Schematic diagram



(b) Vector diagram

Fig 10 Q4: Load with capacitive kVAR (Voltage regulators)
(a) Schematic and (b) Vector diagram

4. Impact on transformer performance for all four quadrants

The life expectancy of a transformer varies depending on many factors and aging transformers are potentially subject to an increased risk of failures. Considering the median age of the large power transformers in the US is about 38-40 years old [5] and most of the interconnecting transformers may not have been designed to accommodate the reverse power, there is an immediate need to study the impact of the reverse power on the transformers. As described earlier, the magnetizing flux in the transformer core established through the excitation voltage (E) which is derived for all four quadrants of operation described in above section. For Q1/Q2, the core excitation is delivered by grid and for Q3/Q4 excitation is delivered by DER. Considering the grid per unit voltage is constant, excitation voltages for Q3/Q4 is always higher then design values which increases the core flux density under those scenarios. The operation of these four quadrants are transformed to the rated active power (forward +ve, reverse –ve) and with reactive power ranging from –0.8 (lag/+Q) to +0.8 (lead/–Q). The load voltage 'V2' for substation transformers are usually set 5% higher to compensate for voltage drop on the feeder. Transformers are optimally designed closer to the knee point of the magnetizing curve of the core therefore, with small increase in excitation voltage (E), the magnetizing current and magnetic losses increase significantly. Usually Magnetizing current is very low for transformers, two-fold increase will not cause issue, however increased core losses will impact the thermal and hence the life of transformers. Also, the core type transformer has three limbs as shown in fig. 11 which does not provide zero sequence flux path. Two different utility company cases for a substation transformer with the customized design D1 (1.63T) and the optimized design D2 (1.72 T) for renewable interconnects for various operating power flow conditions (4Q) are considered and compared in this paper. For the two designs, D1 and D2; the variations in per unit magnetizing current and core losses are shown in dotted line and solid lines respectively in fig.12. At per-unit excitation, the magnetizing current and core losses are considered as per unit as shown in fig. 12.

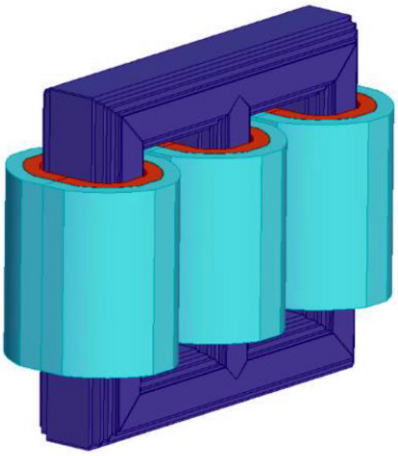


Fig 11 Three-limb transformer core

When increased excitation voltage to 1.15 pu, the magnetizing current is increased to 2.5 and 3.5 pu for designs D1 and D2 respectively. The core losses are increased to 1.4 and 2.0 pu for designs D1 and D2 respectively. For both designs D1 and D2, the short circuit impedance is considered as 9%. These two designs are modified for short circuit impedance of 15%. The increase in excitation voltage and core losses for all the four designs are shown in fig.13.

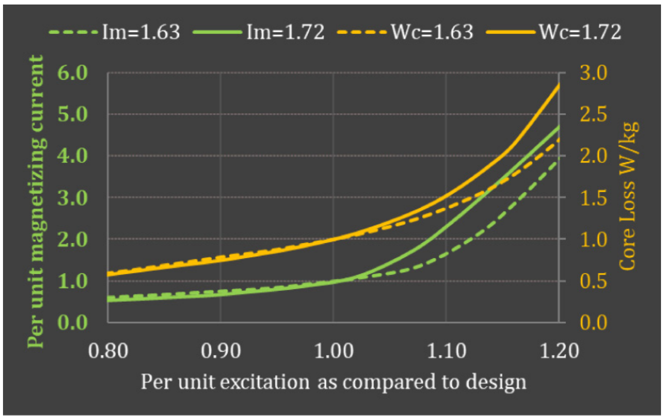


Fig 12 Variation of magnetizing current and core losses with excitation voltage

Results of four design combinations shown in figures 13 to 16, having six (6) load conditions [S1 = Rated forward power flow; S2= Rated reverse power flow; S3 = 133% of rated forward power flow; S4= 133% of rated reverse power flow; S5 = 166% of rated forward power flow; S6= 166% of rated reverse power flow].

Results of figures 13 to 16 indicate that the optimized low-cost design with higher flux density and higher short circuit impedance has more variation in magnetizing currents and core losses. The load terminal voltage is kept 1.0 pu for this analysis. If grid voltage is maintained, then the excitation current is further be increased, and the core is saturated. The saturated core further develops the harmonics and losses associated with it. Normally, infinite bus voltage V1 at the grid terminal is maintained resulting in further increase of magnetizing voltage. Also, the shape of the magnetizing current becomes non-sinusoidal and contains significant total harmonics distortions (THD). The increase in THD

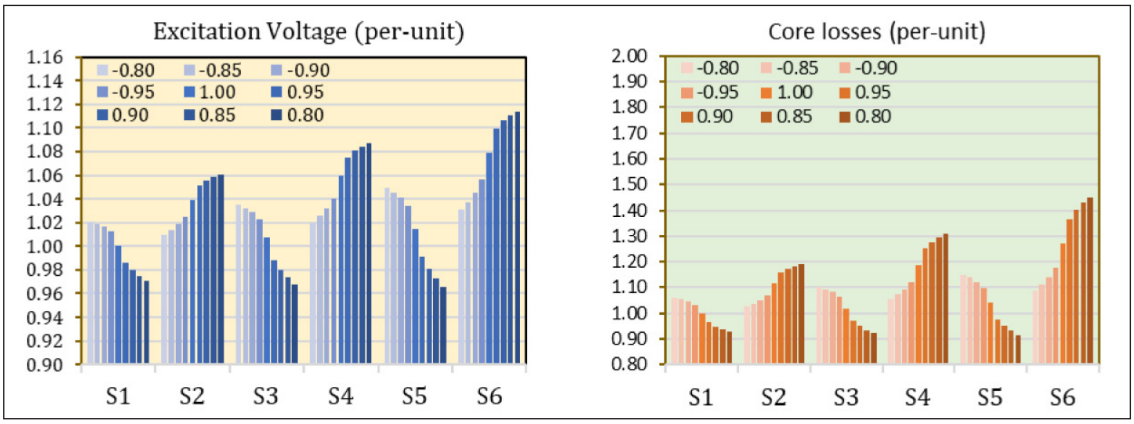


Fig 13 Variation of magnetizing voltage and core losses for design flux density (1.63 T) and short circuit impedance (9%)

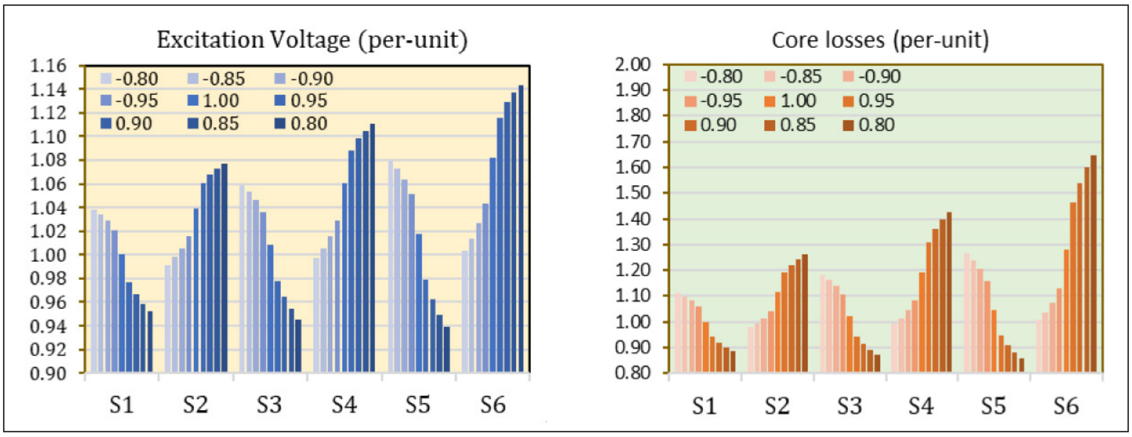


Fig 14 Variation of magnetizing voltage and core losses for design flux density (1.63 T) and short circuit impedance (15%)

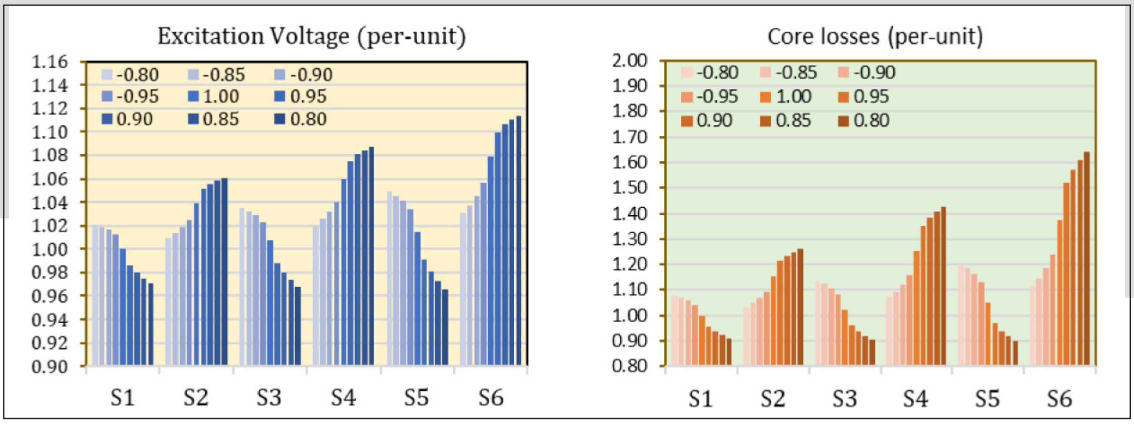


Fig 15 Variation of magnetizing voltage and core losses for design flux density (1.72 T) and short circuit impedance (9%)

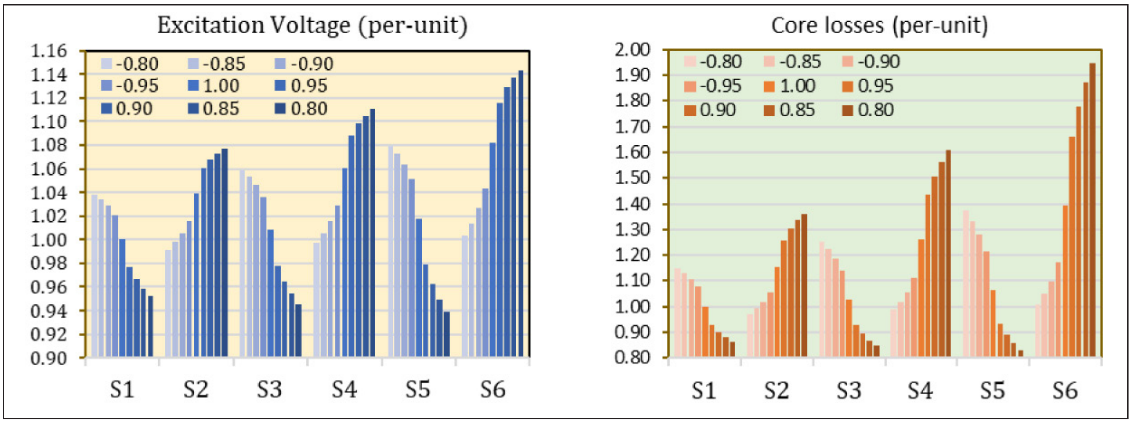


Fig 16 Variation of magnetizing voltage and core losses for design flux density (1.72 T) and short circuit impedance (15%)

leads to higher core losses. The core also saturates if the voltage increases beyond the operational limits. If the power flow is maintained in Q3, then the increase in temperature reduce the life of the transformer (up to 25% loss of life). If the life of the transformer is required to be maintained, then the losses are to be maintained for all the four quadrants as per the nominal design. Therefore, some utility companies impose certain restrictions on developers, manufacturers, service providers, and distributers for reverse power flow through the interconnect transformers (substation transformers and distribution transformers).

5. Potential resolutions

The additional network stresses described above ultimately manifest themselves as stress on the substation collector and generation step-up (GSU) transformers in the forms of increased losses from 1) oversaturation from line- or load-side overvoltage and 2) increased voltage harmonics from the load supply. These stresses will prematurely age the life of the transformer dependent on their amplitude and quantity. Fortunately, transformer manufactures have experience in design to resist these types of stress when the system characteristics are known. Techniques such as increased steps for on-load tap changers, full-load voltage regulators, or reduced flux densities may be used to prevent over-voltage saturation. Integrated inductors and increased k-factor designs can support on reducing the harmonic stresses on the transformer, as well.

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. A system study of the network that accounts for reverse power flow would help improve transformer specifications so that manufacturers can account for and improve transformer design to ensure long-term, reliable power. As an intermediate step to address already installed units, digital technologies to monitor for total harmonic distortion and primary/secondary voltage at the transformer can be installed in order to get better predictability of potential failures and increased aging characteristics.

6. Conclusions

Following conclusions are derived from this research;

1. The phenomena of reverse power flow impact the performance of the interconnect transformers.
2. The transformer losses (core and harmonic) are significantly increase even at 15% higher excitations.
3. For any design, reverse active and reactive power flow condition (Q3) observes maximum core losses for any load conditions.
4. If the reverse power flow is not restricted, then interconnect transformer losses its life by 25%.

5. The restriction on power factor of reverse power flow can maintain the life of transformer.
6. The amount of impact on transformer life depends on design of the transformer and operating conditions.
7. System studies that account for over-voltage and increased harmonics caused by reverse power flow can be used to improved transformer specifications and design.

7. Bibliography

[1] *Renewables 2019 - Global Status Report 2019.*

[2] *Mapping progress as EU states work towards 2020 energy targets, May 2019.*

[3] *State Renewable Portfolio Standards and Goals, National Conference of State Legislatures January 2019.*

[4] *The 14 models of corporate sourcing, Sonia Dunlop, SolarPower Europe, Re-source Nov-2018. [5] Impact of Renewables on Substation Transformers, ABB Power Webinar, May 2019.*