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PS1 - Experience and New Requirements for Transformers for Renewable Generation

Reverse Power Flow Impacts for Legacy Power Transformers

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SUMMARY

Reverse power flow reflects the change from traditional large distant power generation to large urban load centres being upset by renewable generation being connected into power grids at multiple points. According to the IEEE C57.12.00-2015 standard, power transformers are to be designed for step down operation unless stated otherwise - such as for generator step up transformers or system intertie transformers (which are to be designed for step up or step down). According to the IEC 60076-1-2011 standard, the flow of power must be indicated at the time of transformer specification. Thus, many legacy transformers have been designed for power flow in only one direction. New transformers can be designed for whatever reverse power flow situation is required. The focus of the paper was on the thermal implications due to reverse power flow of legacy transformers. The impact on legacy transformers due to reverse power flow is determined by modelling the revised leakage flux pattern and recalculating the winding and core temperatures. The leakage flux pattern can change significantly with reverse power flow for multi-winding or auto connected transformers with tap changer windings. Higher harmonics due to power conversion for renewables or battery storage can lead to greater eddy and stray loss in the transformer which in turn can increase the winding hot spot temperature and core/clamp temperatures. Cases with detailed thermal calculations showed examples of increased winding and core clamping temperatures for reverse power flow and higher harmonics. Cases were also shown for different transformer types (shell versus core type) which were impacted differently for reverse power. Reverse power flow is often not a simple power direction change but can be active & reactive power change as well. Typically, several new reverse power flow scenarios (with load, direction, power factor per terminal) may occur and need to be investigated. Change in power flow can thus have the following impacts to legacy power transformers: 1) leakage flux patterns leading to temperature increase in the core, core clamping, tie plates; 2) winding heating; 3) limited tapping range; 4) reductions in nameplate rating for different loading scenarios; 5) higher harmonics and 6) frequent and rapid transformer temperature changes. The changes to the power grid causing reverse power flow will have significant impacts to power transformers in coming years and it is important to study the impact for each of the individual affected transformers. Transformers with the same nameplate (i.e. electrical parameters) can be affected very differently by reverse power due to their winding arrangement, core type and leakage flux control. Reverse power flow design studies for transformers can show that certain transformers may not be appropriate for reverse power flow and need to be de-rated, replaced or relocated to prevent significantly increased aging or even failure. It is recommended that legacy transformers have an engineering study performed by the OEM for the new load flow scenarios and harmonics (if applicable) to prevent potential overheating and damage to the transformer.

KEYWORDS

Transformer, reverse power flow

1. INTRODUCTION

The rapid rise of renewable generation and their connection to existing power grids have caused significant change to the traditional flow of power which was distant large source generation to large urban load centres. Power can now flow in a different direction (and the direction can change through the day) than the power grid and the associated large power transformers were originally designed for. This change in power flow – termed reverse power flow – can have unintended and large negative consequences to power transformers.

Industry standards address the required direction of flow for transformers. According to the IEEE Standard C57.12.00-2015 Section 4.18, power transformers are to be designed for step down operation unless stated otherwise - such as for generator step up transformers or system intertie transformers (which are to be designed for step up or step down). According to the IEC 60076-1-2011 standard, the flow of power must be indicated at the time of transformer specification. Thus, many legacy transformers have been designed for power flow in only one direction. This may have been appropriate for the original application, however as noted above, the transformer may in the future be required to also have power flow in the opposite direction (or both directions).

It should be noted that new transformers can be designed for power flow in both directions (whatever is required for the application). This must be specified at procurement for the present or future power flow direction need. The main issue for reverse power flow is thus for legacy transformers (not new transformers) where at the original time of manufacturing it was not envisioned that the power flow could go in a different direction than dictated by the standards or the procurement specification.

The focus of this paper is on transformer thermal constraints caused by the reverse power flow. In some situations, there can also be dielectric concerns with operating transformers in reverse power flow due to unintended transients, however this is outside the scope of this paper.

2. REVERSE POWER FLOW POSSIBLE IMPACTS TO TRANSFORMERS

The major impacts of reverse power flow are best understood by the changes to the transformer leakage flux pattern. Below in Figure 1 is shown an example of calculated leakage for a particular loading condition on a transformer. Transformer design engineers use these plots to calculate the short circuit forces, transformer impedance, winding hot spot temperature, core outer packet temperature, core tie plate temperature, core clamp temperature, tank temperature and tank wall shield temperature (if applicable).

Figure 2 shows a core without windings and top yoke to demonstrate tie plate, core clamp and core outer packets. The “tie plate” is the steel plate that keeps the core legs stiff and connects the core top and bottom clamp. The tie plate must have high mechanical strength for short circuit forces and the weight of the core but does see winding leakage flux causing heating. This tie plate heating must be calculated and limited to safe levels (typically 140 ºC). The transformer designer must balance the contrasting need to make the tie plate mechanically strong enough (i.e. wider and thicker) but also narrow/thin for less leakage flux heating. Similarly, core clamps and the outer core steel packets just beneath the tie plate can also see leakage flux (in addition to magnetisation flux) and have overheating.

Reverse power flow can cause the leakage flux pattern to be very different than the original condition. This can increase the winding hot spot temperature, but it tends to be a larger issue for tie plates, core outer packets and core clamps.

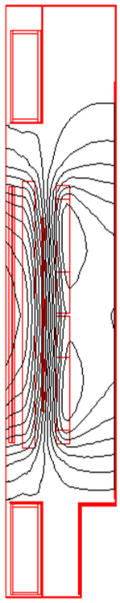

Figure 1 – Example of Modelled Transformer Leakage Flux

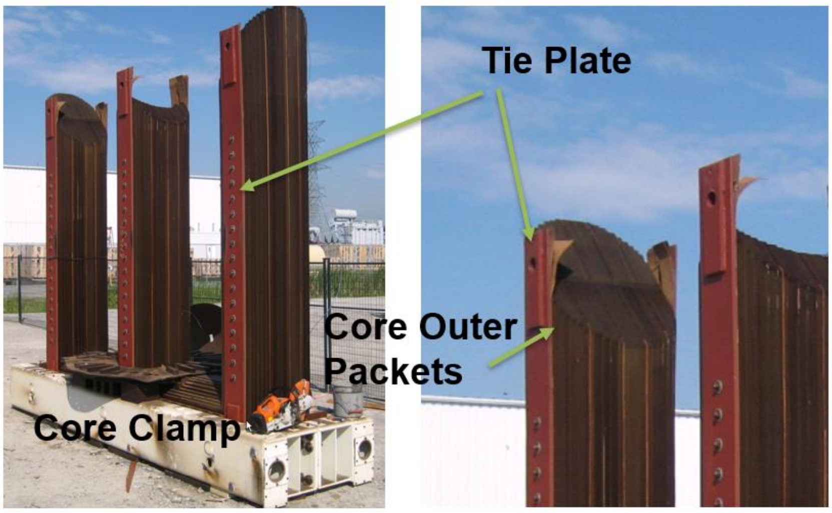

Figure 2- Example of Core Clamp, Tie Plate and Outer Packets

For a simple two winding transformer with no taps, there will be little difference in the leakage flux plot for power flow in either direction (LV to HV, HV to LV). However, with tap windings, extra voltage systems (i.e. TV or 2 LV's), or auto connected transformers with LTC, the leakage flux patterns can become complicated and require multiple scenarios to be modelled. If the power flow direction changes, it is quite possible the leakage flux patterns change enough that there is a large change to the calculated temperatures. If these new calculated temperatures exceed design limits, it then becomes necessary to limit the load under (or avoid) the reverse power flow scenario to prevent damage to the transformer.

The methodology for evaluating a legacy transformer for reverse power flow is as follows:

- Calculate the leakage flux pattern and temperatures (winding, lead, core, clamp, tank) for the original nameplate condition
- Determine the new power flow scenarios (load, direction and power factor per terminal)
- Repeat Step 1 for each power flow scenario
- Check all accessories for each power flow scenario
- Check tapping extremes – it may be required to avoid some tap positions

Change in power flow can thus have the following impacts to power transformers: 1) leakage flux patterns leading to temperature increase in the core, core clamping, tie plates; 2) winding heating; 3) limited tapping range; 4) reductions in nameplate rating for different loading scenarios; and 5) large and frequent temperature changes (thermal cycling).

Again, it needs to be noted that new transformers can be specified to handle whatever power flow situation – the transformer design engineer would model leakage flux for all cases and tapping conditions and design the transformer accordingly to be within design limits. But legacy transformers in many cases need to be studied for their impact to reverse power flow and be potentially derated since it is impractical to change the winding design. The leakage flux must be recalculated for the different power flow scenarios and the resulting winding, core and metal part temperatures examined versus allowed values. While it is predominantly a thermal study, the impact to the tap changer and tapping range must also be studied.

Normally, transformers are calculated for high load power factor (80% or higher per IEEE Standard C57.12.00-2015). However, with renewable generation, energy storage and their connection to the grid at both the transmission and distribution systems, the load power factor can be very different and change frequently. For example, solar farms can put active and reactive power into the network while wind farms can put active power into the network but absorb reactive power. There thus can be various active and reactive power flow situations imposed on the legacy transformer depending on its location in the grid relative to the renewable generation and the time of day. The power flow can be split into the “real” (or active) and “imaginary” (or reactive) components. The leakage flux can be determined for the real and imaginary components as will be shown below.

High harmonics that exceed normal transformer harmonic content (maximum 5% of the rated current per IEEE Standard C57.12.00-2015) can increase eddy and stray loss in the transformer which can increase the winding hot spot temperature and metal part temperatures. Harmonics can be introduced to the load current for example with inverters used in renewables and battery storage. If the transformer was not designed for high harmonic content, then the winding hot spot temperature and metal part temperatures may exceed the limits requiring a derating of the transformer.

Case studies are presented below to demonstrate reverse power flow impact and increased harmonics on legacy transformers.

3. CASE STUDIES OF LEGACY TRANSFORMERS

Below are shown case studies of legacy transformers that are 20 – 50 years old and have operated without issue for many years in the original intended power flow operation. These units were now checked for power flow direction change due to new generation on the secondary voltage system(s). The first 2 cases are shown in greater detail while the other cases are shown more briefly to avoid repetition.

Transformer # 1 - 125 MVA, 230 – 28 – 28 kV, on load taps on HV
This dual low voltage transformer was originally designed for step down operation for HV to both LV’s for the whole tap range. The two LV windings were axially split (top LV and bottom LV) and the HV winding was also split so that in fact each LV fed a respective HV winding half. The leakage flux was managed in Figure 3(a) for controlled core, tie plate and clamp temperatures. The transformer was then requested to operate with generation in one LV system and load in the other LV system (LV to LV). The leakage flux is shown in Figure 3(b)where clearly there are now strong radial flux lines between the LV’s which led to very high core outer steel and tie plate temperatures. The MVA would have to be reduced to 32% load (LV to LV) with all cooling in operation to keep the core and tie plate temperatures to a safe limit.

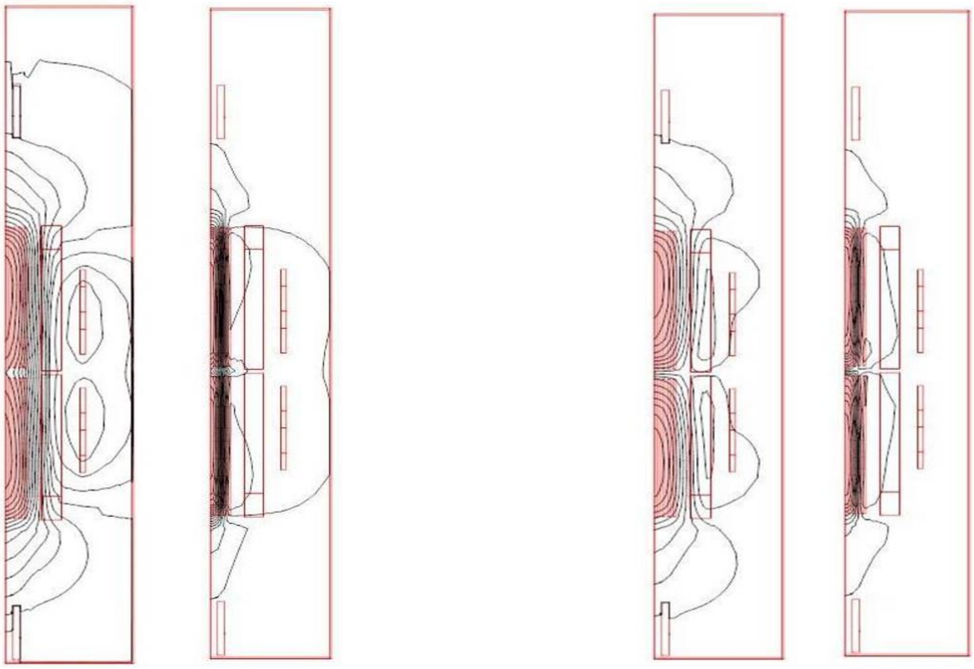

Figure 3 (a) – HV to both LV's (Real & Imaginary) *(b) LV to LV (Real & Imaginary)*

<u>Transformer # 2</u> – 125 MVA, 215 – 28 – 28 kV with on load taps in the HV
This transformer was requested to operate LV to LV with high harmonic load. Harmonic content can be quantified as "K" factor per IEEE Standard C57.110-2008 using the below equation:

$$K = \sum_{h=1}^{\infty}(I_h(pu)^2 \times \mathrm{h}^2)$$

Where I_h (pu) is the per unit rms current at harmonic h
h is the harmonic order

The new harmonic content for the case was estimated to have a K factor of 9. As mentioned above, harmonics increase the eddy and stray loss calculated by the leakage flux pattern and especially increase the winding hot spot temperature. It should be noted that the leakage flux pattern shown below in Figure 4 is calculated without harmonics – the harmonics are included in the post calculations for the winding hot spot temperature and metal part temperatures. With full load at LV to LV and the high harmonic load, the LV winding hot spot temperatures were increased by 23 ºC and exceeded the allowed limits. If the load was reduced to 60%, the transformer would see safe operation.

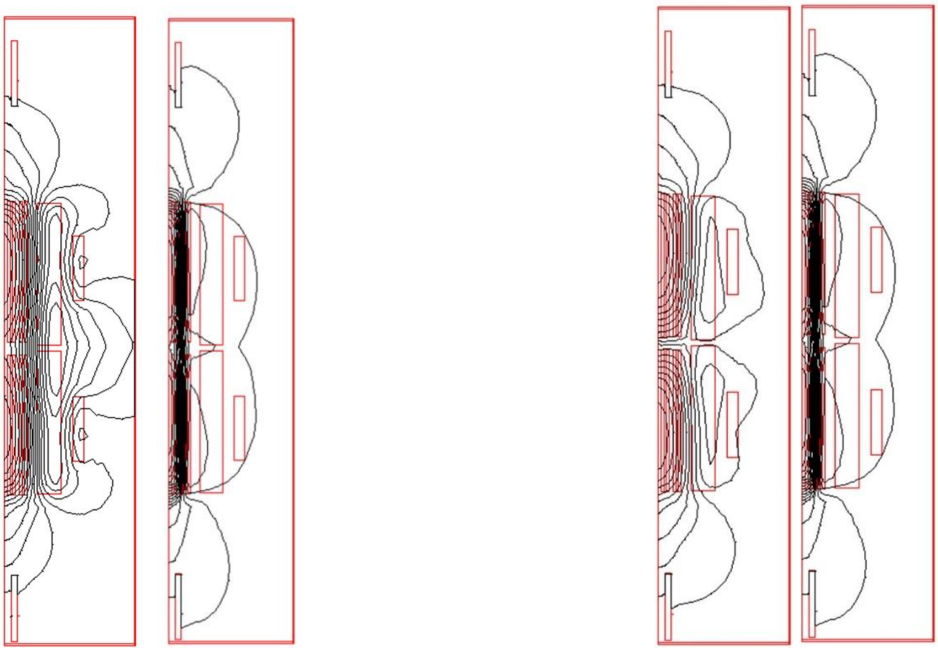

Figure 4 (a) HV to both LV's (Real & Imaginary) *(b) LV to LV (Real & Imaginary)*

Transformer # 3 – 125 MVA, 210 – 28 – 44 kV with off load taps in the HV
This transformer has a similar rating to Transformer # 1 and # 2, however it is a shell type design. It was designed for step down operation (HV to LV's) and the LV's had different MVA (83 and 42 MVA). This transformer was modelled for LV to LV, HV to LV1 and HV to LV2 temperatures and there were no limitations (i.e. no derating). Shell type transformers have a winding design by nature that is more flexible for reverse power flow.

Transformer # 4 - 83 MVA, 240 – 14.1 – 14.4 kV with on load taps in each LV
The transformer was originally designed for step down operation and each LV could independently regulate the output voltage with the independent tap changers. There was also a series transformer and preventative autotransformer for each LV. Several scenarios were requested as shown in Table 1 below for the future power flow changes with each terminal as a possible input. Each of these scenarios was examined for calculated temperatures on the core, clamping, series transformer, preventative autotransformer and the tap changer. All scenarios were found to be within allowed design limits. It should be noted that the load is much reduced from the rated 83 MVA. This example with various scenarios is typical of what reverse power flow requirements might be for a legacy transformer.

Table 1 – Power Flow Scenarios for Transformer # 4

	LV1			**LV2**			**HV**		
Scenario	**P1 (MW)**	**Q1 MVAR**	**LV1 MVA**	**P2 (MW)**	**Q2 MVAR**	**LV2 MVA**	**PH (MW)**	**PH MVAR**	**H MVA**
Original 1			41.5 (output)			41.5 (output)			83 (input)
2	8 (input)	0 (input)	8 (input)	32.4 (output)	5.3 (output)	32.9 (output)	24.4 (input)	5.3 (input)	25 (input)
3	16 (input)	5 (input)	16.8 (input)	16 (output)	1 (output)	16 (output)	0 (output)	4 (output)	4 (output)
4	20 (input)	4 (input)	20.4 (input)	10.2 (output)	4 (output)	10.9 (output)	9.8 (output)	0 (output)	9.8 (output)

Transformer # 5 – 83.3 MVA, 245 – 26 - 26 kV with on load taps in the HV
The transformer was originally designed for step down operation. It was requested to check the operation for generation in LV1 (24 MVA) and output on LV2 (20 MVA) and the HV (4 MVA). It was found that this condition would cause the core outer packets to overheat too much. The allowed temperatures limits could only be met if this condition occurred in winter (20 ºC lower ambient) or the loading was reduced by 5%. Thus, the final allowed load is 55% of the nameplate rating.

Transformer # 6 – 10 MVA, 230 – 13.8 kV with off load taps in the HV
The transformer was originally designed for step down operation but was now required to operate in step up operation with a potential harmonic content (due to new generation on the LV system). It was found that the transformer could operate safely with 9.0 MVA (90% load) in this new condition.

4. CONCLUSIONS

Reverse power flow is a larger concern for legacy transformers since the transformer may have only been designed for power in one direction - per the original specification and industry standards. New transformers can be designed for power flow in both directions.

Power flow can change in both the direction of flow, amount of active vs reactive power and vary throughout the day. This is due to the nature of the load, renewable power and battery storage.

Higher harmonic content can also be introduced to transformers due to power conversion and this can increase eddy and stray loss in the transformer which in turn can increase winding hot spot and core/clamp temperatures.

Cases with detailed thermal calculations showed examples of increased winding and core clamping temperatures for reverse power flow and harmonics. A case was also shown with a shell type design that was not impacted by reverse power flow compared to a core type design.

Change in power flow can have the following impacts to legacy power transformers: 1) leakage flux patterns leading to temperature increase in the core, core clamping, tie plates; 2) winding heating; 3) limited tapping range; 4) reductions in nameplate rating for different loading scenarios; 5) increased harmonics and 6) more rapid/frequent changes to temperature.

It is recommended that legacy transformers have an engineering study performed by the Original Equipment Manufacturer (OEM) for the new load flow scenarios and harmonics (if applicable) to prevent potential overheating and damage to the transformer.

5. BIBLIOGRAPHY

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