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Combining Controlled Switching and Flux Conditioning to Eliminate the Voltage Dips When Energizing the Step-Up Transformer of Renewables and Distributed Energy Resources

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SUMMARY

The switching of power transformers is a notorious source of adverse inrush currents. Such transients are a major impediment to the deployment of renewable energy resources on a distribution system whose short-circuit capacity may not be sufficient to withstand, without harm, the enormous magnitude the inrush currents can reach, generally in the four to ten times nominal amplitude. These in turn tend to cause sizeable voltage sags that system operators cannot risk enduring, particularly when having to restore distribution grids that have seldom been designed to host an ever-increasing number of Distributed Energy Resources (DERs).

Controlled Switching Devices (CSDs, also known as Point-On-Wave or POW devices) that are capable of estimating the magnetization state or “residual flux” of the power transformer they are to energize are customarily used in the high to ultra-high voltage system to mitigate such energization transients by making the circuit breaker close at the very point on the voltage waveform whose prospective flux, defined as the magnetic flux that the grid voltage will impose at the time the circuit breaker closes, fits the measured residual flux of each phase.

A special control method is required to suit the particularities of a medium voltage power grid whose circuit breakers are habitually three-pole gang-operated. This method has proved very efficient at eliminating the energization transients when the power transformer is rapidly de-energized, which is normally the case in a transmission system. However, the efficiency of such method is less when the power transformer de-energization is gradual, as is often the case with the step-up transformer of a Wind Turbine Generator (WTG), Photovoltaic panel (PV) or Battery Energy Storage System (BESS), due to the presence of spinning DC-AC inverters solidly connected to them on their low voltage side.

This paper discusses a novel method combining transformer flux conditioning and controlled switching to eliminate in full the magnetization inrush currents, and the collateral voltage dips, when energizing a renewable or distributed energy resource’s step-up transformer. The results of a thorough experimental demonstration are presented.

KEYWORDS

Controlled Switching, Transformer Flux Conditioning, Inrush Current, Rapid Voltage Changes, Distributed Energy Resources, Renewables, Grid Resilience.

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INRUSH CURRENT AND MITIGATION WITH A 3-POLE GANG-OPERATED BREAKER

The root cause for the transformer magnetization inrush currents is a well-documented core saturation phenomenon when re-energizing a power transformer whose iron core remained magnetized to a certain level, known as residual flux, after it was last de-energized [1]. As an illustration, Figure 1 provides a digital recording of the three currents when energizing, randomly, the power transformer of the Dune-du-Nord wind farm, in Québec's Magdalena Islands. It shows that the current reached 4.5 p.u. (4.5 times nominal current of the power transformer) on that energization. More importantly, the non-controlled energization of this 10 MVA transformer would cause sizeable voltage sags (in inset) on Hydro-Québec's local system.

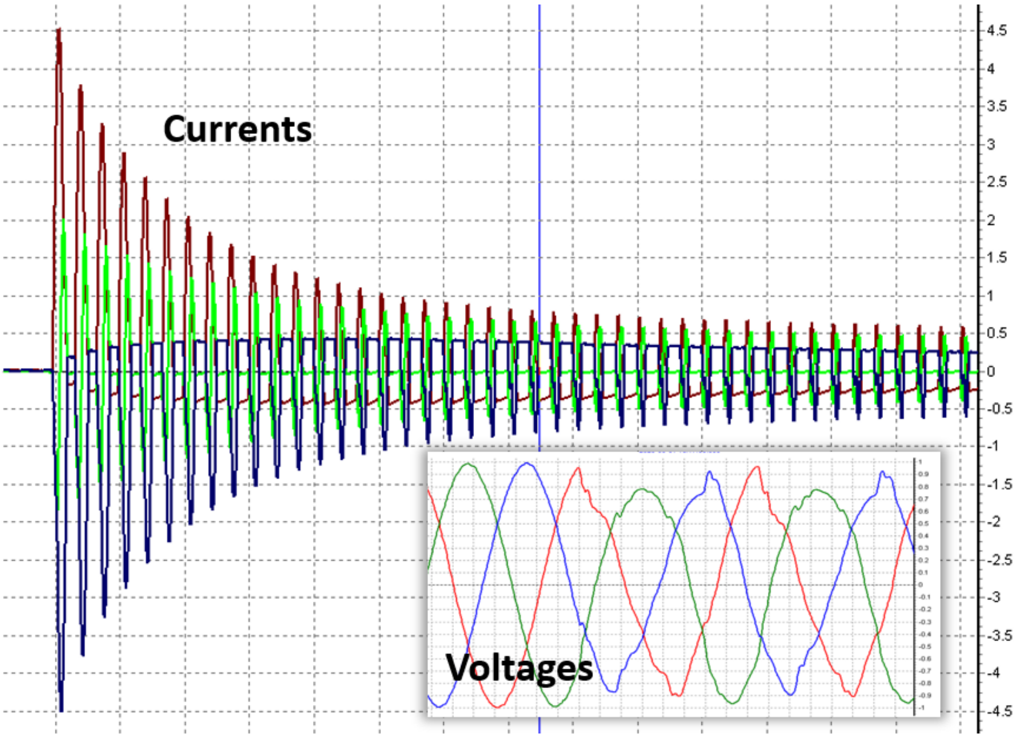


Figure 1: Inrush current and voltage (in inset) when energizing randomly a 10MVA power transformer

On the high voltage grid where independent-pole operation (IPO) circuit breakers are generally used to energize the power transformers, CSDs mitigate such inrush currents by making each pole close at the exact point on the voltage waveform whose prospective flux matches the residual flux in the corresponding phase. In the last decade, a method was developed for a similar, transient-less, energization of medium voltage power transformers through three-pole gang-operated circuit breakers [2, 3]. This method determines the point on the voltage waveform whose three-phase distribution or "pattern" of prospective fluxes is the closest to the magnetization state of the iron core of the de-energized power transformer. Thus, when a transformer is left de-energized with a normally contrasted flux pattern, e.g., +0.6 p.u. on phase A, and -0.3 p.u. on the others, one can always find a point on the voltage waveform where the inrush current is low in all three phases. Such minimum inrush closing point or angle is illustrated Figure 2, where the expected inrush current (in absolute value) for each phase is distributed over the cycle for a given transformer and flux pattern.

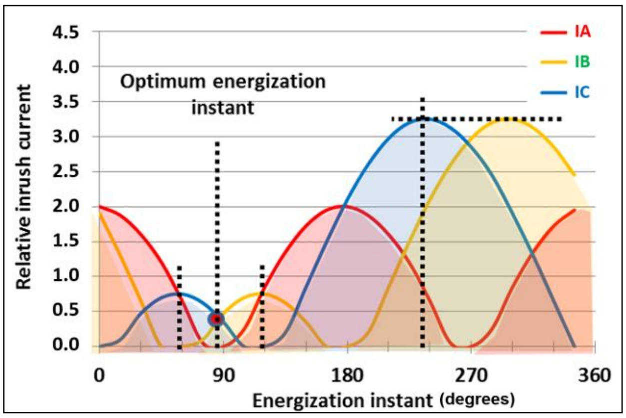


Figure 2: Expected inrush current vs. closing angle for a given pattern of residual flux

Figure 3 shows that a controlled energization of the same 10 MVA power transformer, using a strategy for three-pole gang-operated circuit breaker, causes virtually no switching transients (neither inrush currents nor voltage dips).

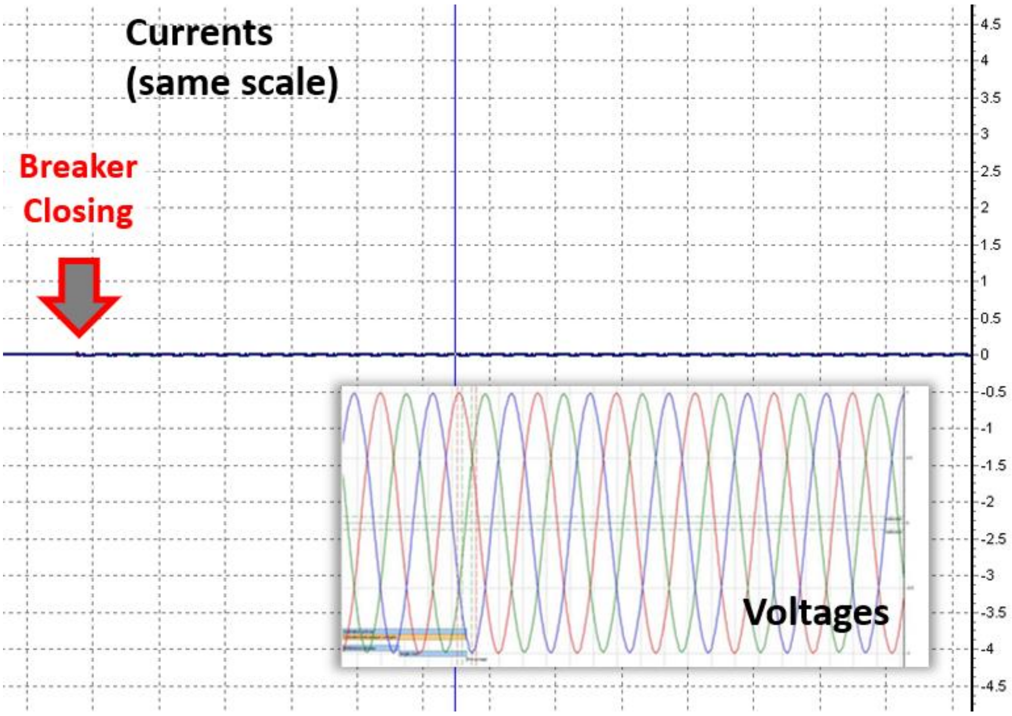


Figure 3: Three currents and voltages (in inset) upon controlled energization of same 10MVA transformer

One important remark regarding this closing is that it was recorded before the rest of the wind farm was commissioned. At that time, the wind farm's highly capacitive underground collector system and, above all, the inverters of the WTGs had not been connected. This allowed for a very rapid collapse of the voltage, leaving a contrasted pattern of residual fluxes (the residual flux being proportional to the mathematical integral of the voltage collapse).

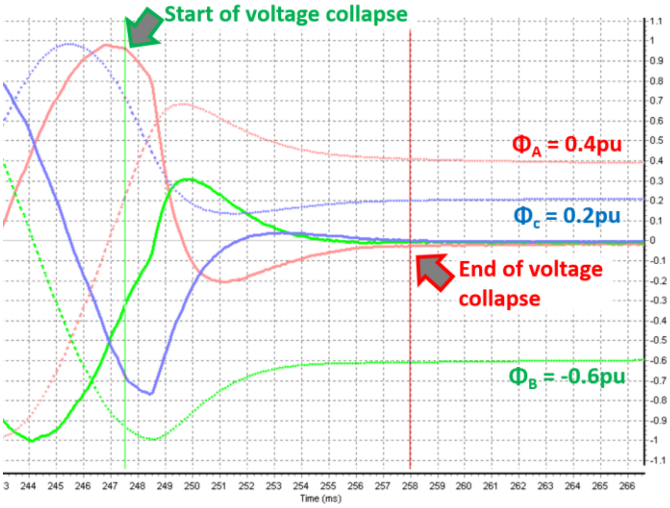


Figure 4 shows that the voltage actually collapsed (solid lines) in approximately 10 milli-seconds on the de-energization of the transformer having immediately preceded the energization of Figure 3, leaving the three cores of the power transformer with a nicely contrasted residual flux pattern (dotted lines) of +0.4, -0.6 and +0.2 per unit, as calculated by the CSD from voltage measurements taken on a side of the step-up transformer.

Figure 4: Recording of the voltage collapse and flux settling on the preceding de-energization

This remark is important because the strategy for three-pole gang-operated circuit breakers leverages the difference in residual flux between phases. As a matter of fact, higher and more different or contrasted residual fluxes are easier to match with a voltage source – the power grid – whose three phases may only be simultaneously synchronized.

IMPACT OF GRID POWER LOSSES AND DC-AC INVERTERS

This controlled energization method for three-pole gang-operated circuit breakers gives very conclusive results and benefits when the power transformer's iron core ends up strongly magnetized following its de-energization, as is normally the case in a transmission or distribution system. This strong magnetization is due to the fact that the only sizeable magnetization source, the grid's voltage (illustrated by a red arrow Figure 5), gets instantly removed, when the breaker trips.

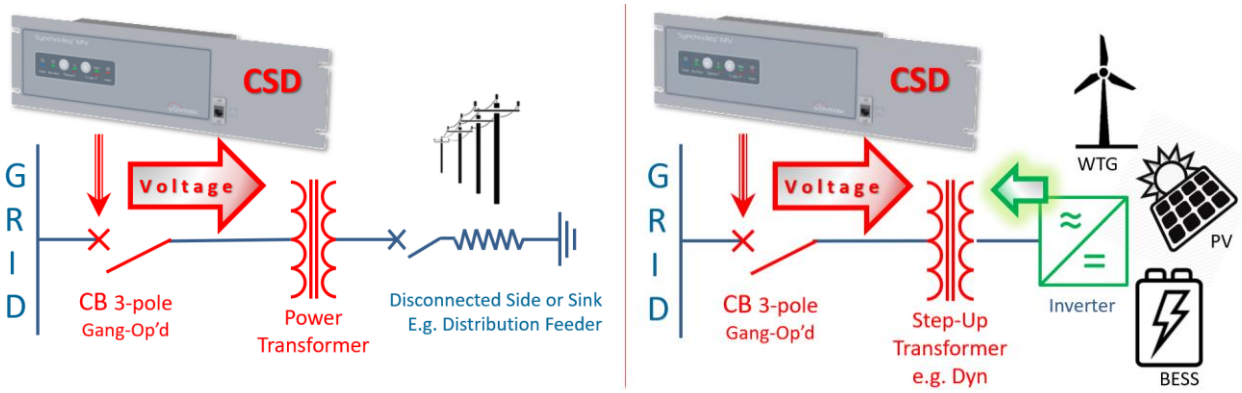
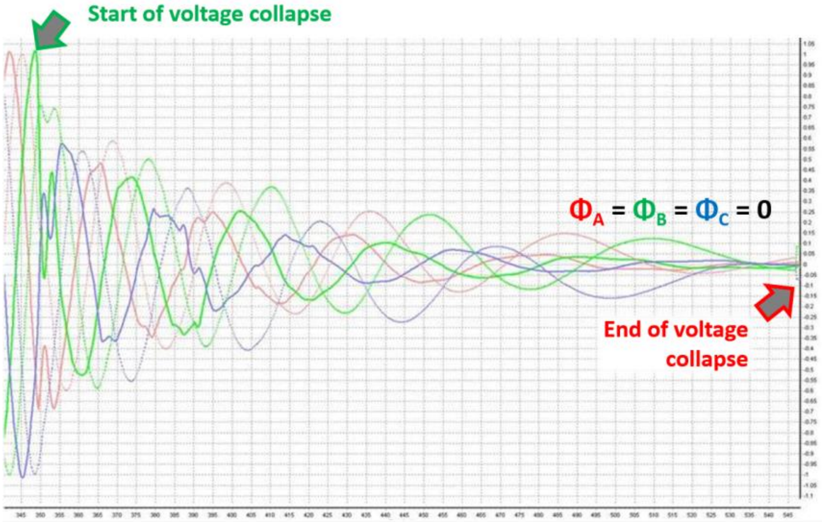


Figure 5: Transformer energization in a typical distribution system (left) vs. renewable (right)

Unfortunately, this method loses a part of its efficiency in the case of the step-up transformer of renewable energy resources during loss of power events and under certain conditions. The reason is that such resources are generally connected through highly capacitive underground collector systems and DC-AC inverters whose trapped charges and power electronics keep feeding for some time the step-up transformer beyond tripping point as illustrated by a green arrow Figure 5. This slowly decaying backdoor voltage in turn demagnetizes the iron core of the connected transformer in the course of its de-energization.

Figure 6 shows the 200+ milli-second long voltage collapse, as recorded by a Vizimax CSD, following the tripping of the step-up transformer at the toe of a windmill in Belgium. The very slow voltage collapse due to the inverter's gradual stoppage consequently caused a zeroing of all three fluxes.

Figure 6: Recording of the slow voltage and flux collapse on a WTG's step-up transformer



This sets at naught this difference in residual flux of which the CSD strategy for three-pole gang-operated circuit breakers draws a sizeable part of its power. Indeed, while the inrush current may reach much higher levels with a normally (i.e., heavily) magnetized transformer, high residual fluxes may also allow for lesser levels of inrush current [2, 4], provided the circuit breaker closes on the right point on the voltage waveform.

Figure 7 shows the expected range of inrush current (Y-axis is for the highest of the three phases' peak in per unit) as a function of the residual flux (X-axis is for the highest of the three flux values), as estimated from the characteristics of the Belgian wind turbine's step-up transformer and short circuit capacity at the point of connection. The ascending red curve shows the highest level of inrush a non-controlled closing may cause, the descending blue curve the lowest, all values in per unit. The grey area in between denotes the field of possibilities when random energizing the power transformer. The red dots are actual CSD-controlled closing events.

The closings on the right side, circled in green, were all following a de-energization with no connected inverter, while the ones on the left side, circled in blue, all followed a de-energization with the inverter on, as in the case of Figure 6. While the most harmful closing possibilities, in orange, were systematically avoided, this diagram evidences the negative impact of the transformer's demagnetization on the performance of the CSD mitigation.

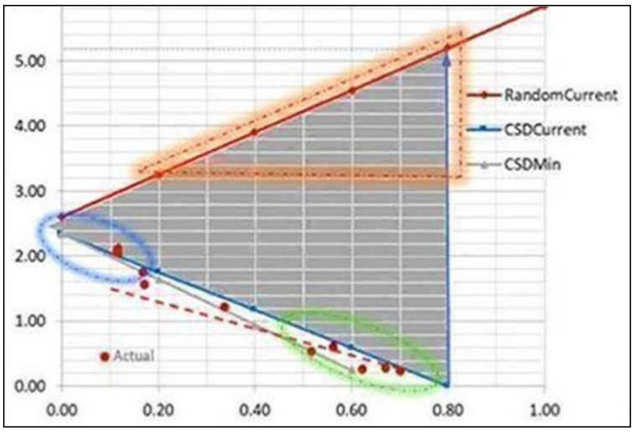


Figure 7: Range of maximum inrush current as a function of the level of residual flux

IMPACT MITIGATION BY MEANS OF FLUX CONDITIONING

The proposed method to mitigate the negative impacts of demagnetizations consists in the forced magnetization or "conditioning" of the power transformer's three limbs to a flux level that is a function of the vector group of the transformer and that corresponds to a right-most point on the diagram Figure 7. This forced magnetization is achieved by the injection (in blue Figure 8) of a CSD-calculated combination of signals on the power transformer's low side connectors. The closing itself is then controlled (in red Figure 8) by the CSD, at the point on the voltage waveform matching the flux pattern installed by the conditioning. For instance, the conditioner would install a pattern of residual fluxes such that the CSD would achieve a fully effective mitigation when re-energizing a Dyn5 transformer at 180 degrees (more precisely 180 degrees after a falling edge zero crossing of phase A's voltage).

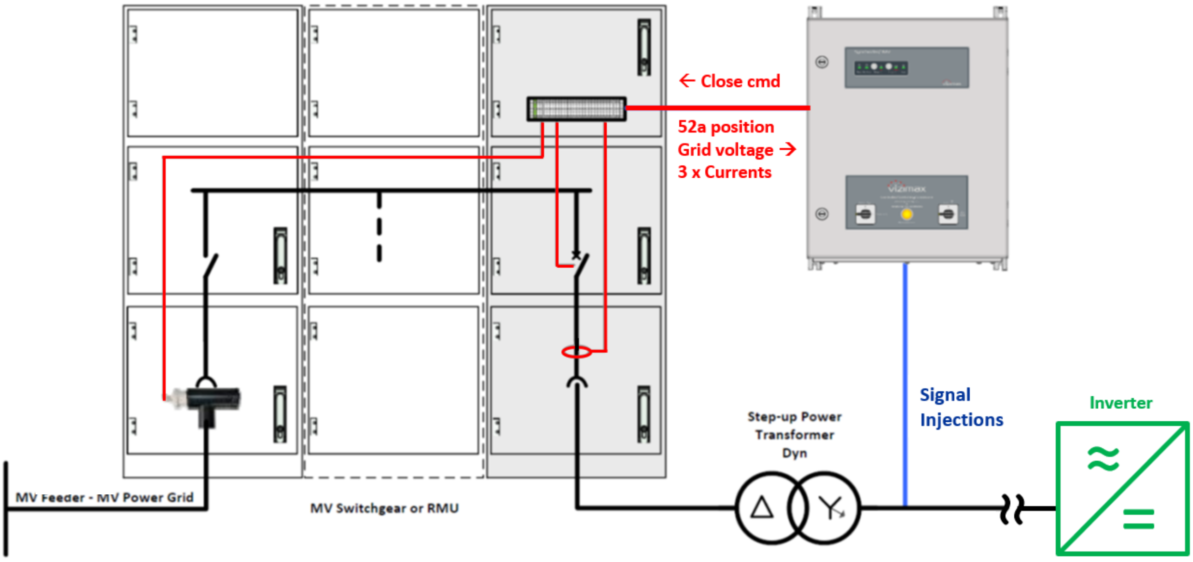


Figure 8: Typical set-up for a medium voltage switchgear installation

The flux conditioning may be automatically activated, when the conditions are met, after a de-energization, or manually initiated, for example prior to a first energization of the power transformer (because the residual flux is normally unknown on the very first energization) or following DC tests having potentially impacted the residual fluxes in the core.

TEST SET-UP

The solution was tested using a set-up very similar to this depicted Figure 8, with a genuine 3-limb 15kVA power transformer and an Insulated-Gate Bipolar Transformer (IGBT) in lieu of a regular Vacuum Circuit Breaker (VCB). The rationale for this change is that the micro-second accuracy of an IGBT would allow us to perform a controlled emulation of the mechanical scatter of VCBs in such a way to verify the performance of the solution under a broad variety of VCB performance scenarios. The selected transformer would also permit testing the six vector groups in the Dyn range (meaning a delta arrangement on primary side, and a grounded neutral secondary), these being very customary for medium voltage step-up transformers in the field of renewables.

A first series of tests was conducted to verify that the response (and saturation) of the selected power transformer was standard, exhibiting the typical triangle-shape distribution of inrush currents as a function of the residual flux we experienced with the Belgian wind turbine (Figure 7).

Hundreds of closings were performed for this, as summarized Figure 9. The red curves (resp. the blue curves) depict the envelope of the observed levels of inrush currents (Y-axis, highest of the three phases' current peaks in p.u.) obtained under the entire spectrum of residual flux conditions (X-axis, highest of the three flux values in p.u.) when the closing was not controlled (resp. was CSD-controlled), the solid lines denoting the envelope's upper limit, the dotted lines the lower limit. This power transformer was proven to behave, from that standpoint, as any regular step-up transformer.

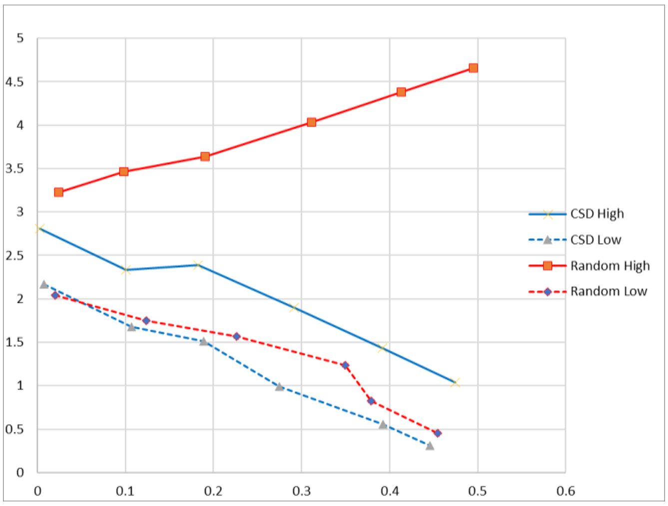


Figure 9: Range of maximum inrush current as a function of the residual flux with the test transformer

EXPERIMENTAL RESULTS

The performance of the solution was first checked with a fully de-magnetized transformer and for all six Dyn arrangements (Dyn1, Dyn3, Dyn5, Dyn7, Dyn9 and Dyn11). Table 1 shows that the highest peak on the three phases was found systematically less than 0.1 p.u. no matter the winding, when applying a closing accuracy of 1 µs, meaning with a circuit breaker exhibiting virtually no mechanical scatter. This table, along with the Dyn5 example Figure 10, evidences that the solution works no matter the vector group (in the Dyn category).

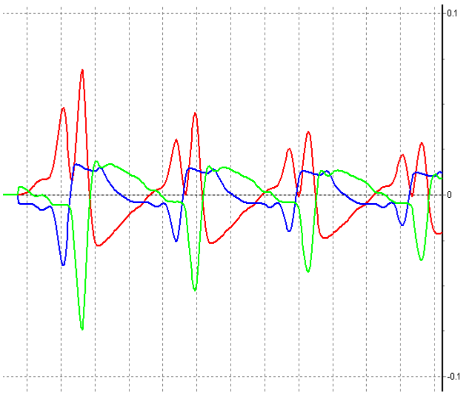


Figure 10: Inrush currents (in p.u.) with a Dyn5 winding

Winding Arrangement	Dyn1	Dyn3	Dyn5	Dyn7	Dyn9	Dyn11
Worst Inrush Current	0.097 p.u.	0.065 p.u.	0.075 p.u.	0.068 p.u.	0.076 p.u.	0.086 p.u.

Table 1: Inrush current per type of winding (no initial residual flux, no mechanical scatter)

The conditioning was also found to work no matter the initial distribution of residual fluxes. To verify this, the transformer was de-energized via controlled breaker trips at every single one of the 360 degrees of a cycle in order to produce a variety of residual flux distributions and residual flux magnitudes. The transformer was then conditioned and re-energized. All tests were conducted twice. Figure 11 shows that the solution exhibits a good performance no matter the opening angle, with an average inrush current of 0.1 p.u. and a worst recorded case of 0.12 p.u.

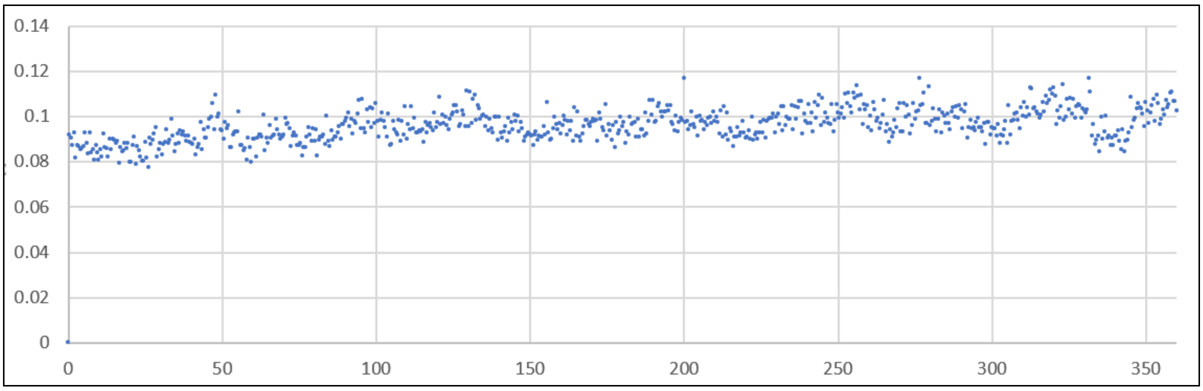


Figure 11: Highest inrush current (in p.u.) as a function of the opening angle (in deg) with a Dyn1 winding

Finally, the solution was tested with a "forced" mechanical scatter to verify both its continuity and overall practicality. This was done by programming a CSD closing error sweeping the entire cycle.

Figure 12 shows the results obtained with a Dyn5 winding. For such vector group, the CSD conditions a flux pattern for which the ideal closing angle is 180 degrees (from falling edge zero crossing of voltage phase A). This figure shows not only that the inrush current is virtually eliminated at 180 degrees, as expected, but also that this target point is stable, since it is the middle point of a very flat plateau (in green) of approximately 50 degrees in width (2.31 ms on a 60Hz system).

Figure 12: Highest inrush current (in p.u.) as a function of the closing angle (in deg.) with a Dyn5 winding

Plateaux of a similar width and flatness can be observed with all six vector group arrangements. This indicates that the solution is to provide excellent mitigation performance with any medium voltage switchgear fitted with a 3-pole gang-operated circuit breaker, either with SF_6 or vacuum interrupter elements. Spring-loaded breaker mechanisms with DC-powered control circuits, as well as pole motion mechanisms consisting of electro-magnetic actuators, are demonstrably suitable for such applications and provide sufficient operation time stability.

CONCLUSION

Combining controlled switching and flux conditioning was experimentally proven to eliminate the magnetization inrush currents when first energizing and re-energizing a power transformer in the Dyn category of vector groups. The continuity and practicality of the solution was also verified assuming a circuit breaker exhibiting an average performance.

This technique appears to be the most promising solution to the problem of magnetization inrush currents and voltage dips when energizing a power transformer solidly connected to an inverter, as is generally the case with distributed and renewable energy resources.

Vizimax plans to further this research and development effort along two main lines, both planned for the course of 2021:

- Field proving the solution, within the context of an existing microgrid, connected and not connected to a utility's main system.

- Developing and testing the technique for a broader and more complete range of vector groups.

BIBLIOGRAPHY

[1] K.R.M. Nair. "Power & Distribution Transformers Practical Design Guide" (CRC Press, 2021, pages 143-149).

[2] P. Taillefer, L. Poutrain, J. Sanchez. "Limiting Voltage Dips & Inrush Currents When Energizing Power Transformers Controlled Switching of Gang Operated Switches - Theory and Case Study" (2018 IEEE/PES Transmission and Distribution Conference and Exposition).

[3] Working Group A3.35 CIGRE. "Guidelines and best practices for the commissioning and operation of controlled switching projects" (Cigré Reference 757, 2019).

[4] C. Carrillo, E. Diaz-Dorado, J. Cidrás, D. Román Costas, J. Grande, A. Gallego. "Analysis of the Transformer Inrush Current in a Hydro Generator" (2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)).