START&STOP SYSTEM FOR MORE EFFICIENT SMART TRANSFORMERS AT RENEWABLE POWER PLANTS. BEYOND THE ECODESIGN DIRECTIVE

Luis DEL RIO ETAYO
Ormazabal Corp. Tech. – Spain
lre@ormazabal.com

Bittor VILLAMERIEL
Ormazabal Corp. Tech. – Spain
bvv@ormazabal.com

Ibon LARRACOECHEA
Ormazabal Corp. Tech. - Spain
ilz@ormazabal.com

Rafael AGUNSO
Ormazabal Corp. Tech. – Spain
rab@ormazabal.com

Pablo CIRUJANO
Ormazabal Cotradis – Spain
pcb@cotradis.com

ABSTRACT

The Start&Stop system allows Smart Transformers equipped with OLTC to increase efficiency dramatically whilst maintaining their capability to control voltage, thus improving the reactive power capability in renewable power plants to comply with grid codes.

Experimental results show that by means of an innovative pre-insertion resistor, integrated in the OLTC, inrush current is fully mitigated even in the worst-case scenario, without the need of a complex circuit breaker controller.

INTRODUCTION

Energizing power transformers is a critical event in the operation of any electric power system. When a transformer is energized, a large inrush current may flow. These currents have many unfavourable effects, such as undesired protection tripping, deterioration of the insulation and mechanical support structure of windings and reduced power quality of the system, i.e. temporary harmonic over-voltages and momentary voltage dips [1].

Particularly regarding solar plants, transformer inrush causes a voltage dip in the system. This in turn could potentially cause adjacent loads or even entire solar farms to drop off, especially solar farms on a single line, which potentially could cause a pattern of systemic voltage dips. Grid codes are now being revised globally to limit transformer inrush currents and ensure speedy reconnection after a trip.

STATE OF THE ART

There are several techniques for the reduction of transformer magnetizing inrush current:

<u>Controlled switching</u>
The residual flux plays a significant role in the development of the magnetizing inrush current. Its value can be influenced by means of point-on-wave controlled de-energization of the transformers.

Without controlled switching, the energization may occur at any time on the voltage wave producing a high inrush current peak when the transformer core is driven to saturation.

This technique has been studied both for 3-pole operated breakers with single spring drive and fixed time-delay between the operating poles [2] and for single-pole breakers by closing each winding when the prospective and dynamic core fluxes are equal results in an optimal energization, without core saturation or inrush transients [3-4].

All circuit breakers have some statistical deviation in their mechanical closing time from operation to operation, especially where there is a large variation in ambient temperature range. Timing deviations can lead to a non-optimal inrush current mitigation.

<u>Sequential Phase Energisation Technique</u>
This method uses a grounding resistor connected at a transformer neutral point. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series inserted resistor and thereby significantly reduces the energisation inrush current [5-8].

It requires single-pole breaker coordination at the star of a transformer with a star-delta connection[1].

<u>Virtual Air Gap Technique</u>
The virtual air-gap technique consists in modifying the magnetization characteristic of a magnetic circuit by an additional unidirectional magnetic flux produced by a set of control or auxiliary windings fed by a direct current. This produces zones of controlled magnetic saturation level, called virtual air-gaps, whose effects are very similar to those of devices with real built-in air-gaps [9,10].

The advantage of this method is that the equivalent length of the virtual air-gap can be controlled by the magnitude of the dc current applied to the auxiliary windings, achieving a controlled change in the magnetic core

[1] Usually at the substation end of the transmission line.

reluctance. Its drawbacks are that is difficult to make an appropriate air gap in transformer core and mechanical stability problems can arise [9,10].

Using Superconductor

Superconducting fault-current limiters normally operate with low impedance and are "invisible" components in the electrical system. In the event of a fault, the limiter inserts impedance into the circuit and limits the fault current.

High-temperature superconductors (HTS) can also be used as inrush current limiting elements that suppresses the inrush current using the flux-flow resistance generated in HTS [11].

Pre-insertion resistors (PIR)

One of the factors that leads users to apply closing resistors is the concern that the accuracy in timing of breaker opening and closing in controlled switching may not be achievable, especially where there is a large variation in ambient temperature range [12].

To ensure a satisfactory performance of pre-insertion resistors, for limiting inrush currents during transformer energization, it is crucial both to specify that the minimum insertion time should not be less than about 0.7 electrical cycles [12] and to calculate an optimum resistance value to get a quick decay of inrush current and a low voltage drop, thus allowing a quick by-pass of auxiliary contacts and reduced losses [13].

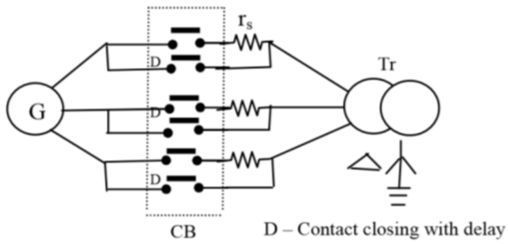

Figure 1. Resistance connected in series to lines with 2 auxiliary contacts per phase [13].

The PIR technology is a well-known and highly reliable solution. However, it requires auxiliary contacts to by-pass large resistors, which additionally need maintenance as they are installed along the electric lines.

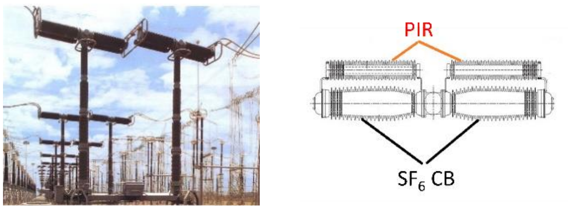

Figure 2. SF_6 circuit breaker with pre-insertion resistors.

SMART TRANSFORMER

A new compact Smart Transformer with a patented (flat) On Load Tap Changer (OLTC), an innovative solution for distribution networks, has been developed. Its flat design provides a compact solution, maintaining the footprint of a conventional distribution transformer (facilitating retrofitting).

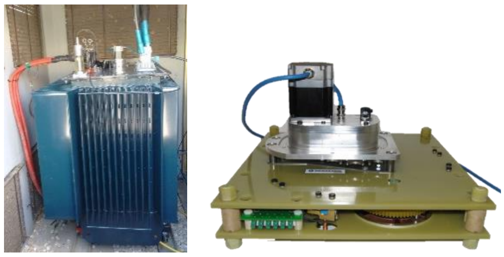

Figure 3. Smart Transformer and its OLTC.

The solution is based on an electromechanical OLTC that can change the transformation ratio of the transformer by adding or subtracting turns from the MV winding. It is able to change the tap position automatically, and with load, by means of a combination of fixed and movable contacts, along with a set of vacuum interrupters (two per phase) on the MV side of the transformer. The vacuum interrupters guarantee that the tap changing is performed safely because the arc, created during the switching process, is located inside the vacuum bottle - preventing oil pollution.

It is not just a VRDT[2] but also a smart transformer because the solution includes a digital sensor for temperature, oil level and internal pressure, that allows an optimal exploitation of the transformer.

The Smart Transformer has been tested in both internal [14, 15] and external laboratories [16, 17], where it successfully passed the required test from International Standards: IEC 60076 – Power Transformers [18], IEC 60214 – Tap-Changers [19], IEC 61000 – Electromagnetic Compatibility (EMC) [20].

It can also use high fire resistant biodegradable ester oil instead of mineral oil.

START&STOP SYSTEM

In order to deal with the former technology drawbacks, a Start&Stop technology is proposed including PIR inside the Smart Transformer, using the existing OLTC vacuum interrupters instead of the auxiliary contacts. Therefore, the OLTC capabilities are used to implement the PIR technology, avoiding maintenance costs as resistors are immersed in dielectric oil.

[2] Voltage Regulating Distribution Transformer.

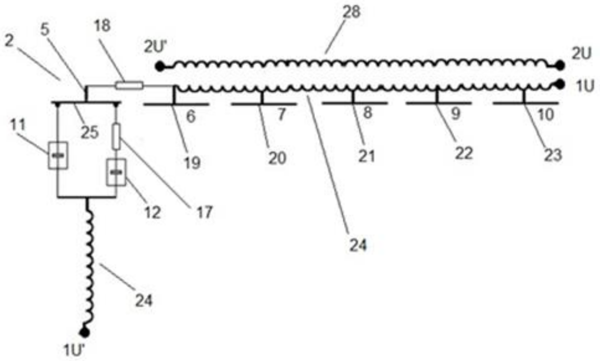

Figure 4. Diagram (from the patent) of the Start&Stop configuration of the OLTC (18. PIR)

Figure 4 shows how the implementation of an additional tap position (Tap "zero") including a PIR system, within the OLTC design, allows the use of vacuum interrupters to by-pass the PIR once the inrush current is over. Afterwards, the OLTC will behave as usual.

Figure 5. Prototype of a Smart Transformer with integrated PIR in delta (primary side).

Renewable power plants application

When transformers at renewable power plants are energized, high inrush currents and overvoltages may be created on the distribution network.

The Start&Stop innovative system facilitates and allows the disconnection of the Smart Transformers in solar farms at night or in wind farms when the wind speed is too low or too high, or when the TSO does not allow more wind energy in the national generation mix (grid stability concerns), avoiding the unfavourable effects of inrush current over transformers.

The Smart Transformer allows renewable power generation plants to comply with grid codes because it can always be supplied with its nominal voltage, thus enabling full reactive power capability use. Therefore, there may no longer be a need for an external reactive power compensation system and there is no need to oversize the inverters or reduce the amount of active power fed to the grid, thus making the generation plant more cost-effective.

BEYOND THE ECODESIGN DIRECTIVE

The disconnection of the Smart Transformer saves the fixed losses, i.e. iron losses, when the smart transformer is not working, thus achieving a high efficient transformer for renewable power plants – even beyond the current Ecodesign Directive [21].

Although the Ecodesign Directive only takes into consideration test losses, the Start&Stop technology allows a large reduction of operational iron losses thus overall smart transformer losses are dramatically reduced when applied to renewable power plants.

For example, the largest planned photovoltaic plant in Europe to be built in the autonomous community of Extremadura (Spain), the 391MW Nuñez de Balboa solar project [22], will have a maximum of 15h of sun light in summer solstice and a minimum of 9.5h in winter solstice. That means that a Start&Stop system would suppress iron losses during at least 9h/day up to 14.5h/day depending on the day of the year.

SIMULATIONS AND TESTS

Several simulations and inrush current tests, to check different resistor technologies, magnitudes and configurations, have been carried out in the ORMAZABAL High Power Lab (HPL) in order to assess the influence of the transformer coil inductance, plus resistors magnitude and location (in series with lines or integrated in the delta connection), over the inrush magnitude. In all the studied cases, voltage disconnection at 90º and connection at 0º was achieved by means of the HPL Synchronous Circuit Breaker (SCB), resulting in the maximum inrush currents (worst-case scenario) in every test.

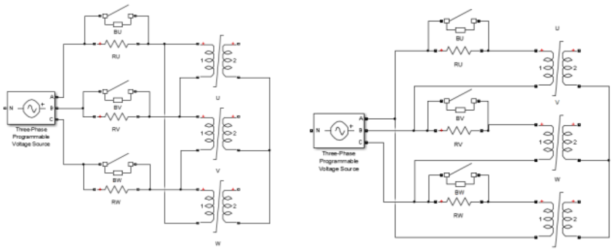

Figure 6. PIR simulation in series with lines (left) and within the delta connection (right).

Figure 7. Smart Transformer with PIR in series with lines (left) and inside the transformer (right).

Residual flux

The magnitude of the residual flux was promoted/calculated in order to obtain the worst possible inrush scenarios. The aim was to demonstrate that the proposed innovative solution works even without a SCB system (able to measure, control and minimize the residual flux).

Residual flux calculations were based on real voltage measurements at both the connection and disconnection times. By means of an adaptation and integration of measured voltages during tests, it is possible to calculate the residual flux in the transformer core in order to assess that the worst inrush magnitudes are achieved.

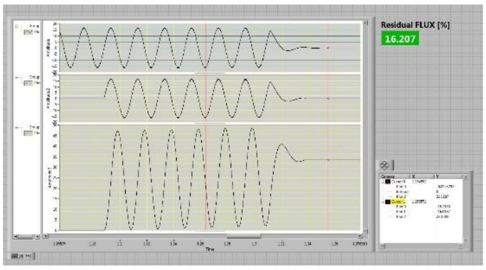

Figure 8. Residual flux calculation example using an *ad-hoc* software.

RESULTS

The following results correspond to: a comparison of the resistance magnitude needed to achieve a similar inrush mitigation when the PIR are in series with lines or integrated within the delta connection at Tap 1 (maximum coil turns), Figure 9; a comparison of inrush mitigation with 1.500Ω PIR within the delta connection versus an smart transformer at Tap 9 (minimum coil turns) with different making degrees, Figure 10; and, an example of the maximum inrush current measured at the HPL at Tap 9 with the SCB connecting voltage at 0º and disconnecting at 90º, Figure 11.

As all tests were performed as worst-case scenarios, real measured inrush currents should be statistically below these maximum values.

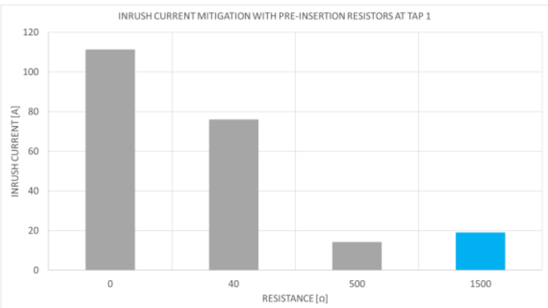

Figure 9. Maximum inrush current at Tap 9. In series with lines (grey) and within the delta connection (blue).

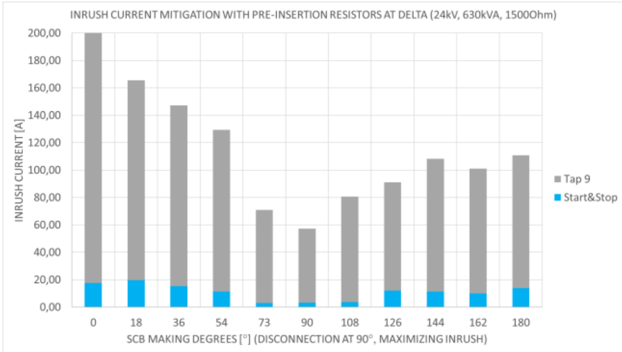

Figure 10. Maximum inrush at Tap 9 vs Start&Stop, with different making degrees and disconnection at 90º.

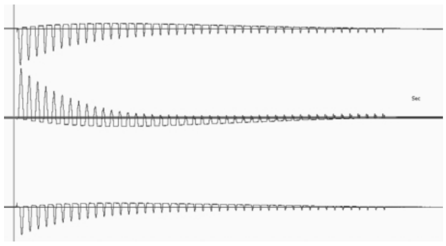

Figure 11. Maximum inrush current at tap 9.

CONCLUSIONS

Experimental results show that by means of an innovative pre-insertion resistor, integrated in the OLTC, inrush current is fully mitigated even in the worst-case scenarios, without the need of a complex circuit breaker controller (retrofitting a Circuit Breaker to achieve a Synchronous Circuit Breaker).

Due to the fact that resistance magnitude within the delta connection has to be roughly 3 times that needed in series with the line, and the high value of such resistance, common wired power resistors are not valid due to a lack of space inside the transformer. Therefore, specially designed power resistors are needed.

The Start&Stop system allows Smart Transformers equipped with OLTC to increase efficiency dramatically whilst maintaining their capability to control voltage, thus improving the reactive power capability in renewable power plants to comply with grid codes.

REFERENCES

[1] S. Shrivastava, A. Khan, A. Mahor, December 2014, "Transformer Inrush Current and Related Challenges", *International Journal of Emerging Technology and Advanced Engineering, vol 4, issue 12.*

[2] L. Prikler, G. Bánfai, G. Bán, P. Becker, 2003, "Reducing the magnetizing inrush current by means of controlled energization and de-energization of large power transformers", *International Conference on Power System Transients – IPST, New Orleans, USA.*

[3] J. Brunke, K. Frohlich, April 2001, "Elimination of Transformer Inrush Currents by Controlled Switching-Part I: Theoretical considerations", *IEEE Transactions on Power Delivery, vol 16, no. 2.*

[4] J. Brunke, K. Frohlich, April 2001, "Elimination of Transformer Inrush Currents by Controlled Switching-Part II: Application and Performance Considerations", *IEEE Transactions on Power Delivery, vol 16, no .2.*

[5] Y. Cui, S. G. Abdulsalam, S. Chen, W. Xu, April 2005, "A Sequential Phase Energization Technique for Transformer Inrush Current Reduction – Part I: Simulation and Experimental Results", *IEEE transactions on power delivery, vol. 20, no. 2.*

[6] W. Xu, S. G. Abdulsalam,, Y. Cui, X. Liu , April 2005, "A Sequential Phase Energization Technique for Transformer Inrush Current Reduction – Part II: Theoretical Analysis and Design Guide", *IEEE transactions on power delivery, vol. 20, no. 2.*

[7] M. Jamali, M. Mirzaie, S. Asghar-Gholamian, 2011, "Mitigation of Magnetizing Inrush Current using Sequential Phase Energization Technique", *Research Journal Elektronika IR Elektrotechnika, no.2 (108).*

[8] R. Moon, R.K. Dhatrak, April 2014, "A Study of Effect of Magnetizing Inrush Current on Different Ratings Of Transformers", *IJAREEIE Vol. 3, Issue 4.*

[9] V. Molcrette, J. Kotny, J. Swan and J. Brudny, July 1998, "Reduction of Inrush current in single phase transformer using virtual air gap technique", *IEEE Transactions on Magnetics, vol.34, No. 4.*

[10] J. Avila-Montes, E. Melgoza, September 2012, "Scaling the Virtual Air-gap Principle to High Voltage Large Power Applications". *2012 XXth International Conference on Electrical Machines.*

[11] H. Shimizu, K. Mutsuura, Y. Yokomizu, T. Matsumura, June 2005, "Inrush-current-limiting with T/sub c/Superconductor". *IEEE Transactions on Applied Superconductivity.*

[12] J. Hu, B. Bisewski, D. Maki y M. B. Marz, 2011, "Mitigation of Voltage Drop Using Pre-Insertion Resistor during Large Transformer Energization in a Weak System: Simulation and Field Verification", *International Conference on Power, Delft.*

[13] K. Basu P. y A. Asghar, 2008, «Reduction of Magnetizing Inrush Current in a Delta Connected Transformer", *Power and Energy Conference, 2008. IEEE 2nd International, Johor Bahru, Malaysia.*

[14] L. Del Río Etayo, J. Alcorta, A. Soto, A. Ulasenka, S. Aranaga, P. Cirujano, G. Pérez de Nanclares, October 2016, "A New Compact Smart Distribution Transformer with OLTC for Low Carbon Technologies Integration", *ARWtr 2016 – La Toja Island*.

[15] L. Del Río Etayo, P. Cirujano, P. Lauzevis, A. Soto, A. Ulasenka, G. Pérez de Nanclares, June 2017, "A New Smart Distribution Transformer with OLTC for Low Carbon Technologies Integration", *CIRED 24th International Conference on Electricity Distribution, Glasgow*.

[16] L. Del Río Etayo, P. Cirujano, A. Ulasenka, I. Larracoechea, R. Brandl, G. Arnold, November 2018, "Integración de Transformadores Inteligentes en Plantas de Generación Renovable garantizando su Operación después del ensayo de Hueco de Tensión (LVRT)", *Jornadas Técnicas de Comité Nacional de España.*

[17] R. Brandl, G. Arnold, L. Del Río Etayo, A. Soto, A. Ulasenka, I. Larracoechea, P. Cirujano, G. Pérez de Nanclares, June 2018, "Assessment of the Low Voltage Ride-Through capability of a smart distribution transformer with OLTC for renewable applications", *CIRED workshop WORKSHOP 2018 on Microgrids and Local Energy Communities*.

[18] IEC 60076-1:2011. Power transformers.

[19] IEC 60214-1:2014. Tap-changers.

[20] IEC 61000-4-1. Electromagnetic compatibility (EMC).

[21] Commission Regulation (EU) No 548/2014 of 21 May 2014 - Directive 2009/125/EC of the EP and of the Council with regard to small, medium and large power transformers.

[22] https://renewablesnow.com/news/iberdrola-signs-solar-ppa-with-spains-uvesco-633490/