TERNA FLEET MANAGEMENT OF POWER TRANSFORMERS: THROUGH FAULT CURRENT MONITORING TO PLAN PROPER MAINTENANCE

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ABSTRACT

One of the main causes of power transformer failure in the Italian transmission grid has been ascribed to unpredictable external events, including over-voltages, lightning strikes and through fault currents. The latter ones are supposed to be the indirect cause of winding displacement on autotransformers and of electrical failures of transformers interconnecting HV and MV grids. The paper offers an overview of a through fault current (TFC) monitoring system and the results of a trial performed on a TERNA HV/MV transformer. The purpose of the trial was to detect over-currents and demonstrate that most events occur without the utility being aware. The record of such activities will allow to rank the transformer fleet, improve maintenance schedule, correlate multiple on-line data and extract new parameters to be added to the TERNA Health Index.

INTRODUCTION

For several years, the recorded failure rate with all the TERNA transformers in operation has been considerably less than 1%. In recent years, while the fault rate has increased, the average age of failed units has decreased [1]. This trend led TERNA to develop a strategy to ensure the required level of reliability and safety of large power transformers, including on-line monitoring, control and reduction of external electrical stress, specification and testing. An in-house bespoke Health Index has been adopted [2], set up on the combination of external parameters (keraunic level of the site, substation layout, recurrence of catastrophic events on that site, etc.) and transformer parameters obtained through onsite testing and laboratory results.

Keraunic level and the occurrence of through fault currents are sensible parameters considering that lightning strikes and external short circuits contribute to about 30% of transformer failures [3]. Keraunic level is already included into the TERNA Health Index while the occurrence of through fault currents is now under investigation.

Speculations were made in literature [4-7] about the aggregate effects of through fault currents on transformers, potentially able to produce mechanical stresses which result in the progressive weakening of the winding clamping pressure and, thus, movement of the winding turns. These sorts of over-currents (typically >50% of maximum short circuit current) can produce electromagnetic forces, proportional to the square of the peak of the fault current, which can weaken the mechanical structure to a point where the transformer is no longer capable of withstanding a short-circuit at its terminals. This can lead to severe winding displacement. Inter-turn short circuits are also a possible consequence of the movement of the winding disks.

A new on-line diagnostic parameter is currently considered to identify those transformers with less capabilities to withstand a short-circuit current.

A trial project was run in 2015-2016 through the installation of a monitoring device able to record any kind of over-current, extract key parameters, calculate the energy (I^2t) and the aggregated effects (cumulative I^2t). The idea behind this system is to setup alarms based on both the peak and rms level, plan the inductance measurement just on those transformers mostly affected by through fault currents and define the testing schedule depending on the event magnitude and cumulative energy.

BACKGROUND

TERNA Test Procedure

Winding deformation has been recognized to be one of the most critical issues affecting the Italian transmission network, leading TERNA to establish a solid campaign of winding inductance tests on their transformers.

TERNA own about 677 power transformers which are undergone to winding inductance test every 4 years if in good condition; in case of variation of the inductance the following rule is adopted:

- $\Delta L>1\%$, the test is performed every year;
- $\Delta L>2.5\%$, schedule transformer replacement;
- $\Delta L>5\%$, take the transformer out of service.

This campaign allowed to:

- assess that about 10% of transformers were affected by winding deformation;
- schedule the replacement of 6 units with severe deformation (>2.5% inductance variation measured).

In several cases this was not enough to save the transformers due to the unpredictable nature of the short circuit events.

Limitations of Disturbance Recorder

Disturbance recorders are widely installed in the Italian transmission network.
These devices:
- are activated by the protection relays, when protections are armed
- are driven by the protection relay, not by the current itself
- capture data depending on relay settings
- are generally used to support a post-failure investigation; not for predictive maintenance or condition monitoring
- do not record inrush currents
- do not send any notification
- do not send any data
- do not extract any parameters automatically; they just store waveform in COMTRADE format

Therefore, the Operation and Maintenance (O&M) personnel are unaware of the total number and magnitude of the short circuit events affecting the transformers. The notification of a short circuit event is sent from the control centre to the O&M only if a protection trip allows the primary breaker to open. It is then up to the O&M personnel to go on site and manually extract the data from the disturbance recorded. A typical scenario is when a lightning strike causes a short circuit in the HV line, which is cleared within 100ms and the breaker is reclosed immediately. In such a case the notification of the event is not sent anywhere, even if the transformer has faced a potentially very high over-current.

Case Study #1 – mechanical stress resulting in winding deformation

A critical inductance variation was measured in a 160 MVA autotransformer, exceeding 5% in one phase.
As per TERNA internal procedure, a transformer with inductance variation >5% must be taken out of service. Note that the previous measurement, carried out 4 years before, had shown perfect results. Disturbance recorders were manually interrogated by TERNA experts to investigate the possible reasons for such a significant variation; it was found that the phase with a larger inductance variation had experienced, few months before the measurement, a through fault current with an rms value 86% of the maximum short circuit current, Icc. The event had been recorded by the disturbance recorder since the protection was armed, but not notified to TERNA because the fault had cleared before the transformer relay could trip. It has been speculated that the transformer had experienced a significant amount of through fault currents over its life that could have reduced the mechanical strength in a way that it was not capable to withstand an event of such a magnitude.

Case Study #2 – mechanical stress resulting in electrical failure

TERNA owns about 133 transformers which interconnect the HV network to the MV grid. The protection at the MV side are managed by the Distribution System Operator (DSO). Whenever a short circuit occurs at the MV side, the DSO clears it before the transformer HV breaker opens, refer to Figure 1. These faults that can potentially cause high currents through the HV/MV transformer are not notified to the TSO because the transformer HV protection relay does not open or because the disturbance recorders are not even installed on TSO side. Therefore, the TSO is unaware of how many events and of which magnitude have affected the transformer, unless the HV protection has tripped.
A 32 MVA transformer has recently experienced a failure within the MV winding insulation (summer 2016). Electrical tests were carried out on the failed transformers, showing turn-to-turn short circuit. At least two other similar cases had occurred in the past 10 years. Also in this case, the repetitive occurrence of through fault currents has been speculated to be the main cause of the failure, having caused the inter-turn insulation to degrade due to continuous winding movement.

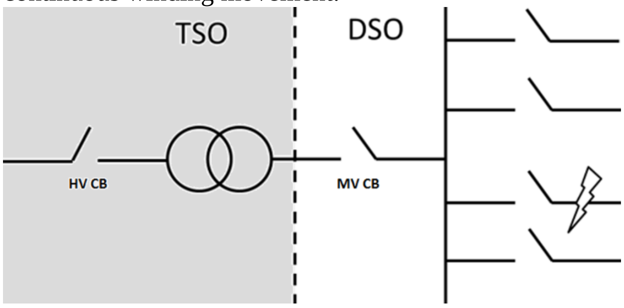

Figure 1: Typical HV/MV configuration. Failures at the MV side cause TFC on transformers, but are notified to TSO only if HVCB opens

TRIAL PROJECT

Description of the system

The monitoring system (Figure 2) detects and stores over-currents exceeding a configurable trigger and evaluates parameters such as duration time, RMS, maximum peak, energy of the event (I^2t) and the aggregated effect of the over-currents (cumulative I^2t). Waveforms are stored and available in COMTRADE format; notifications are sent to the O&M when events are triggered. The sensors are three hall-effect clamp type CTs, installed in the control room cabinet (Figure 3) on the secondary winding of HVCTs.

Figure 2: TFC monitor installed in TERNA control room

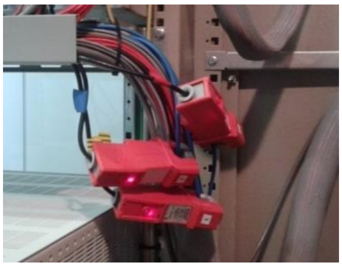

Figure 3: CT clamp sensors at the secondary winding of the current transformer

Figure 4 shows the records from the disturbance recorders (top) compared to the one from the monitoring device (bottom) after a short circuit occurred at the MV side. The two readings match perfectly, thus validating the TFC monitor sensitivity and accuracy.

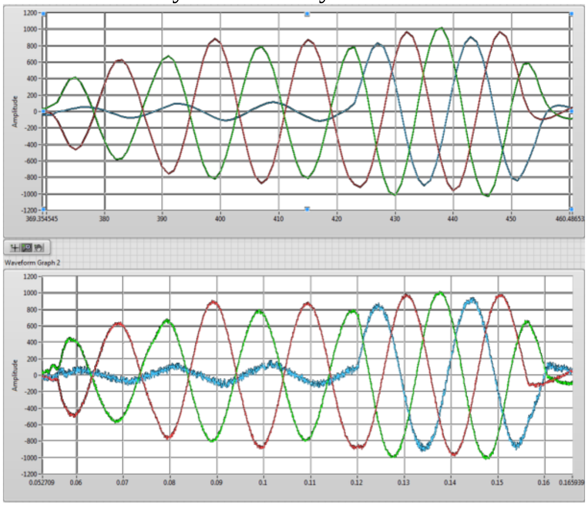

Figure 4: Comparison between the disturbance recorder (top) and TFC monitor (bottom) readings showing perfect matching

Results

A trial project has run for 13 months across 2015 and 2016 on a 63 MVA transformer, 220/22 kV (category IV, [8]). Nominal and short circuit parameters of the transformer are shown in Table 1. 41 through fault current events have been recorded during the trial period. Of particular interest are that 7 of them have exceeded the 60% of Icc, 11 events have been recorded in a 2-day time frame and then 8 in a 10-hour time frame. No one of these over-currents has tripped the transformer out of service or even triggered the transformer protection since all of them have been cleared by MV protection; for this reason, TERNA would not have been aware of the stresses suffered by the machine if the TFC monitoring system had not been installed.

Figure 5 shows one of the records detected during the monitoring period. It is a short circuit between two phases that evolves into a three-phase failure. The RMS is about 70% of Icc and the duration does not exceed 100ms. The event is related to a short circuit occurring in the medium voltage network and cleared by the MV protections before HV ones are activated.

Table 1: Short circuit parameters

Parameter	Description	Value
I_N	rated current	165 A
$V_{cc}\%$	short circuit impedance	13.1 %
Icc	maximum short circuit current (symmetric)	1260 A
Icc_{peak}	first peak of the maximum short circuit current (asymmetric)	3401 A
T_{max}	maximum time the transformer can withstand Icc with no irreversible damages [8]	2 s
E_{max}	maximum short circuit energy ($Icc^2 \cdot 2$)	3173 kA^2s

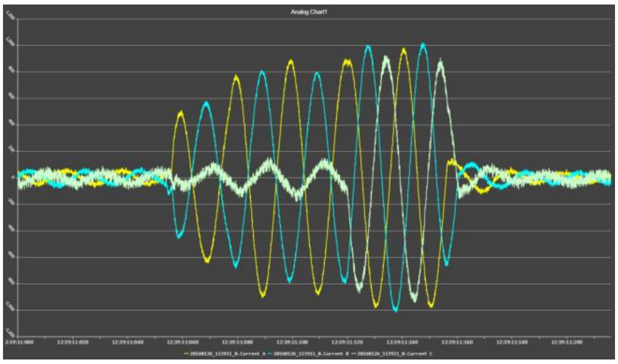

Figure 5: Short circuit at MV side recorded by the TFC Monitor

Figure 6 shows an inrush current detected by the TFC monitor. This is an interesting event in terms of electrodynamic forces. These events are not triggered by protection relays and, thus, not recorded by disturbance recorders and not notified to TSO.

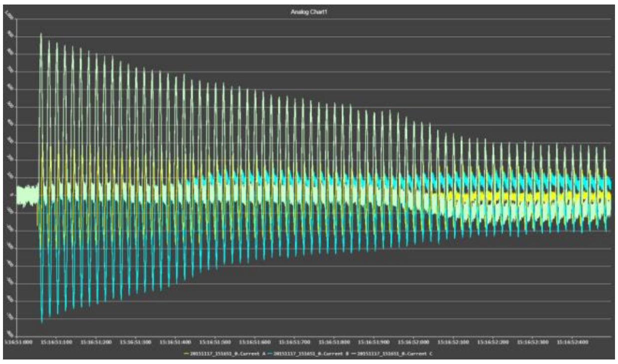

Figure 6: Inrush current

Figure 7 shows the historical occurrence of the through fault current events, plotting the RMS in p.u. of the maximum Icc and cumulative energy (I^2t) in p.u. of the maximum energy Emax as per Table 1 [9-12], while Figure 8 shows the maximum peak in p.u. of the Iccpeak. The peak has been always under the 50% of the Iccpeak, while the rms of several events have exceeded 60% Icc and, in several cases, it has been close to 80%.

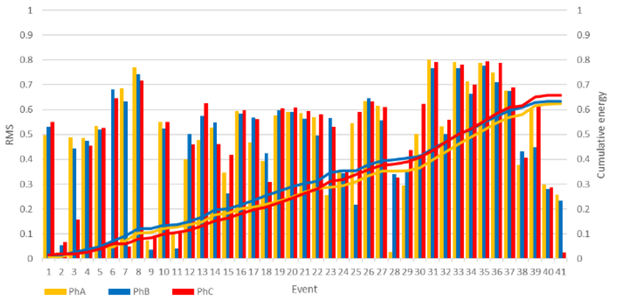

Figure 7: RMS in p.u. of Icc and cumulative energy in p.u. of Emax on the event base

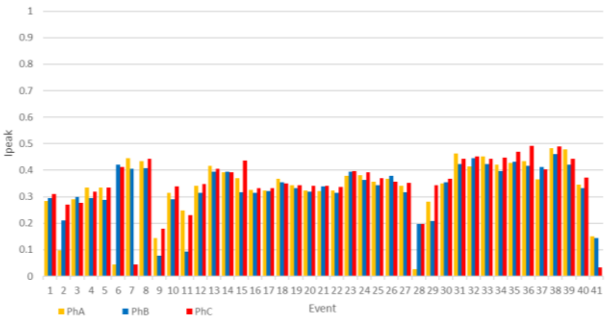

Figure 8: I peak in p.u. of Iccpeak on the event base

Figure 9 shows the cumulative I^2t in p.u of Emax over time. Note that the cumulative energy had two steps around 7 July and 24 November due to the highly repetitive occurrence, respectively 11 in 2 days and 8 in 10 hours. These were likely due to repetitive circuit breaker reclosing attempts at the MV side.

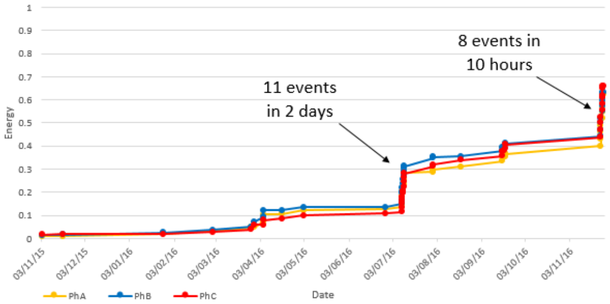

Figure 9: Cumulative energy in p.u. of Emax on the time base

Practical implication and future developments

TFC monitoring system can help TERNA to better schedule electrical tests basing on events suffered by transformers. SFRA, DC winding resistance, winding reactance and DGA analysis can be planned when the TFC monitoring system rises a warning.

Warnings can be set:

- on the base of the amplitude event, as an internal criterion in TERNA, electrical tests could be planned whenever an event exceeding 80% Icc is recorded. Trigger will be set on the trends in Figure 7 and Figure 8. A first warning when the RMS reaches 80% of Icc and when the Ipeak reaches 60% of Iccpeak;
- on the theoretical maximum withstanding capability, which means when the plot of Figure 9 reaches 1 p.u.

TFC monitoring is now integrated into a global transformer monitoring which includes dissolved gas analysis, bushing monitoring and partial discharge. With this system, all monitored parameters can be sent to TERNA on event base, e.g. every time an over-current (exceeding a certain trigger) is detected. Indeed, correlation of multiple on-line data aimed at providing meaningful information on the transformer condition is a key feature for the fleet management.

Another interesting application of the TFC monitor is the inrush current monitoring of HV shunt reactors. These apparatuses are increasingly used to control the reactive power in the transmission network and they are often operated daily.

Circuit breakers must be perfectly synchronized to prevent critical inrush currents. Figure 10 shows the inrush currents with a faulty synchronizer. One of the currents is asymmetric and has a peak higher than in the other two phases.

The TFC monitor can detect such anomalies tracking and evaluating the misalignment over the time between voltage peak and contact closing, i.e. a warning may be generated based on current peak and/or misalignment.

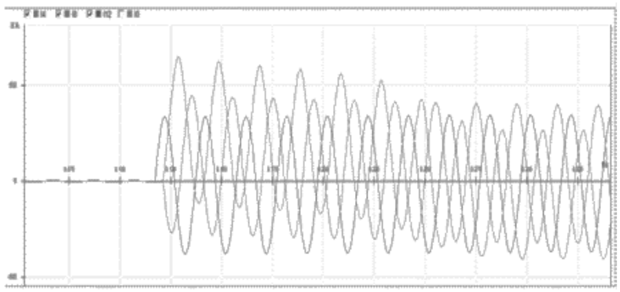
Figure 10: Inrush current with faulty synchronizer on shunt reactors

CONCLUSION

The experience demonstrates that transformers are repetitively affected by induced mechanical stresses caused by through fault currents that fault recorders do not reveal and which could critically jeopardize the winding and blocking their system integrity and reliability. It demonstrates as well that the asset owner is, in most cases, unaware of the electrical and mechanical stresses affecting the transformer, therefore, unable to schedule further investigation and/or corrective maintenance.

TFC monitoring is a valuable feature for TERNA to rank the transformers based on external event occurrences. Data can be then correlated to other on-line diagnostic parameters, especially DGA, to plan condition-based off-line tests and maintenance.

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Massimo Rebolini joined ITALTRAFO in 1978 and then served ENEL from 1980 to 2000 initially as expert in Electrical System following the design and construction of electrical system of NPP mainly in the qualification class 1E of electrical components. From 1988 to 1996 was appointed as Project Manager following the HVDC Interconnection between Italy and Greece. Afterwards was appointed in 1997 as responsible of HV Sistems (Substation and OHL) in Enelpower company until 2000 when enter in GRTN (Italian Independent System Operator). He was appointed as Project Manager for Preliminary Project and Permitting Procedures for interconnection 380 kVca between Italy and Switzerland (S. Fiorano – Robbia) and for SAPEI Project (new HVDC link between Sardinia and Mainland Italy). In 2006 was appointed as Head of Preliminary Projects in Terna Planning and Grid Development Direction following all the main strategic works until 2009 when assumed the actual responsibility of Development Technologies. Author of several national and international technical papers, he is coordinator member of Electrical Energy Transmission WG, advisor of AEE (Associazione Energia Elettrica) and Chairman of Italian Cigrè.

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Enrico Savorelli was born in Forlí (FC) on 1980 May the 12th. He received the M. S. degree in Electrical Engineering from the University of Bologna in 2007. From 2003 he has been mainly involved in research activity and field services on diagnostic of insulating systems by Partial Discharges (PD) analysis. In 2012 he joined Camlin Power Ltd, part of the Camlin Power group, in Northern Ireland, where he is involved in developing PD monitoring systems for Medium and High Voltage assets. He is currently Product Manager for the HV products.

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