For different reasons, one or two phases supplying the power transformer can get to open phase condition while transformer is in operation

ABSTRACT

This article deals with open phase events in power transformers, mainly related to nuclear power plants where several cases have led to a global initiative for a prompt solution for this vulnerability. Different solutions are possible, and one of them, which has already been tested at a Spanish nuclear power plant, is presented here. Field test results are presented together with simulations.

KEYWORDS

power transformers; transformer monitoring; open phase operation; nuclear power plants

Detection of open phase condition in power transformers

Transformer monitoring: Open phase condition

1. Introduction

Power transformers are key components in nuclear power plants and have a clear impact on the operational safety. Some transformers supply critical components in the plant where safety is a first priority. Most transformers are supplied by a three-phase system. For different reasons, one or two phases supplying the power transformer can get to open phase condition while transformer is in operation.

This is an Open phase condition event (OPC). Standard protection systems may not detect this situation because the transformer magnetic core restores the voltages in the affected phase, hence not tripping the protection devices. This situation cannot

Standard protection systems may not detect open phase condition because the transformer's magnetic core restores the voltages in the affected phase

lead to serious damage of the transformer, but if loads like motors are connected to the secondary side, those can end up being supplied by an unbalanced system leading to an over temperature trip or possible damage, depending on their own protection mechanisms.

A relevant open phase condition was first recorded in Byron Station (Illinois, USA) 2012 and several other incidents have been reported since then [1]. This has resulted in an international need to define the problem and design upgraded solutions to avoid it, either at an operational, protection, or electrical level.

Subsequently, similar events occurred in several nuclear power plants and, together with a review of the operational experience, it was concluded that open phase problem should be studied in greater depth. This resulted in the WANO (World Association of Nuclear Operators) SOER (Significant Operating Experience Report) 2015-01 "Safety Challenges from Open Phase Events" [5], in which the possible non-detection of the event by the existing electrical protection systems is identified and how that influences important safety equipment.

The NRC (Nuclear Regulatory Commission) has established the criteria by which the protection design and its ability to tackle the OPC phenomenon will be evaluated, with the Standard Review Plan, BTP-8.9 (Branch Technical Position). The NEI (Nuclear Energy Institute) has developed an initiative to give a proactive response from the nuclear industry to the problem. The VGB (International technical association for generation and storage of power and heat) has coordinated studies of motor behavior in an OPC [6] and has made recommendations to install new protections. They recommended detection of the OPC phenomenon by measuring the voltage or reverse sequence current protections (47, negative sequence overvoltage protection and 46, negative sequence overcurrent protection) [7].

In the case of Trillo Nuclear Power Plant in Spain, the applicable regulation is RSK 467 (Reactor Security Commission of Germany) [8], in which the necessary actions are established, that must be undertaken by the plants. It permits protecting security equipment without including new equipment in the reactor protection system, because it presupposes that there is no qualified equipment. It also suggests that the OPC can be detected by measuring the voltage or reverse sequence current.

For its part, the IAEA (International Atomic Energy Agency) has issued the safety report "Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants" [9]. It indicates again the recommendation to detect the problem by measuring the voltage or reverse sequence current. It also reflects that the option of detecting a single OPC with toroidal current transformers of higher class and precision for new protections (51G neutral overcurrent protection) [7]

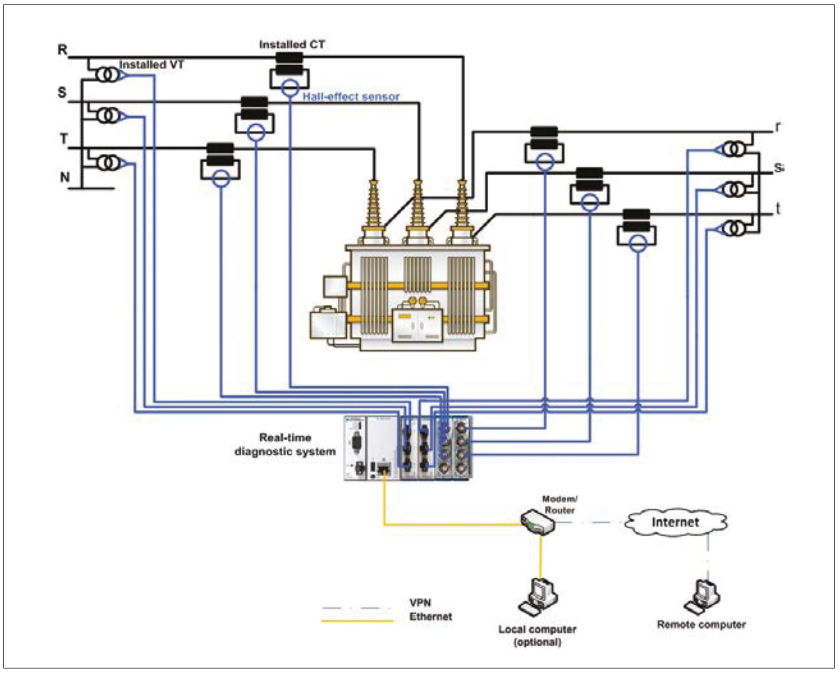

Figure 1. Example of EMS TCM monitoring system. Courtesy of Enging.

that generate alarms only, should be programmable and adjustable depending on the load of the transformer (algorithm detection).

Technology is continuously supporting this evolution and there are different solutions being implemented in each nuclear power plant. The idea is to have a 100% coverage of all possible situations from no load to full load of a power transformer.

2. Power Transformer Monitoring

Traditional maintenance of power transformers was related to field testing program during planned plant outages. Then it was performed as a set of usual tests on the power transformer: DC Insulation, Tan delta, FRA (Frequency Response Analysis), FDS (Frequency Domain Spectroscopy), etc. This work [2] has been upgraded with improved test sets and software support.

Off-line testing has been complemented with transformer monitoring, especially in critical transformers. Actual monitoring systems for power transformers are subject to a continuous evolution in technology. What is demanded in monitoring is noise discrimination, high reliability (if possible with a longer life time than that of the transformer), lesser amount of data to work with (instrument needs to be smart) and reliability in diagnosis. Monitoring Technologies from most common to newer solutions are:

- Dissolved gas analysis (DGA, continuous monitoring)
- Bushing monitors (either testing C1 leakage or on-line tan delta)
- Tap changer evaluation
- Partial discharge measurement
- Current and Voltage monitoring

This last technology lies between protection and monitoring. Systems record data from actual current and voltage transformers to diagnose problems in evolution [3, 4] in the transformer. The advantage is that sensors are already there: current and voltage transformers. Technology is non-invasive, and assumes connecting in parallel to potential transformers and picking a current probe around secondary wires of current transformers.

By using this technology, a Portuguese company named Enging – Make Solutions developed a system that can continuously monitor several variables from voltage and current measurements (Figure 1), compare them with a transformer model and also check magnetization current. This way, the monitoring system can detect and discern if there is a problem either in the windings, magnetic core or tap-changer. The system is called EMS TCM (Transformer Condition Monitor).

3. Open phase solution

Some open phase conditions can be detected with protection relays, but usually either the relay doesn't cover the full range of operation or the protection relay is specially dedicated for the application that makes the cost higher.

In general, international organizations that have analysed the problem, recommend monitoring the phenomenon based on measuring the voltage and reverse sequence current (protections 47 and 46), as well as the currents that are drained to neutral of the transformer connected to ground (protection 51G).

The detection of an OPC simple that affects a transformer in no load, or with a low load, if the neutral on the high voltage side of the transformer is connected to ground, presents great difficulties, since we have voltage levels and reverse sequence current that are very small, regenerating the

Some open phase conditions can be detected with protection relays, but the problem is how to cover the full range of operation or the relay's cost

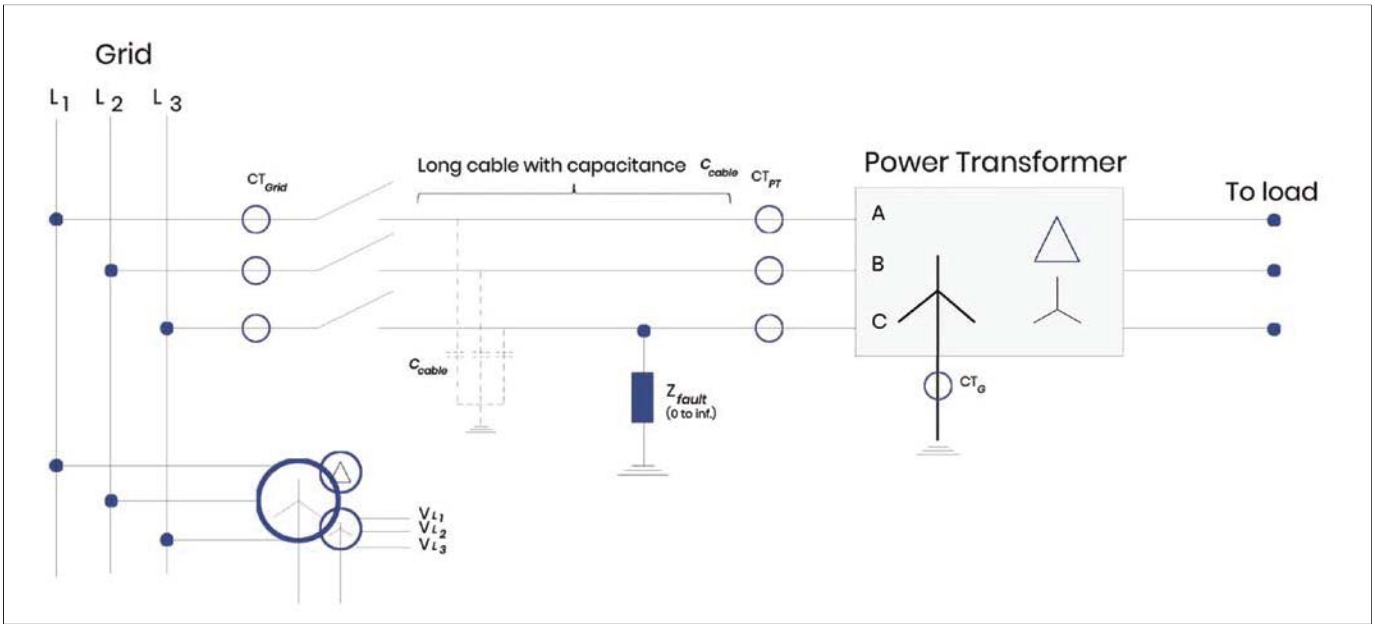

Figure 2. Schematic representation of the system under analysis, for open phase detection (OPD).

voltages and then, neither conventional protections 46, 47 nor 51G can be used.

With an adaptation/extension of the EMS TCM system, the EMS OP-TCM system was developed for open phase event detection.

Enging's OP-TCM is a fully integrated solution designed to solve a problem that has appeared in the nuclear power industry: how to detect open-circuits faults for off-site auxiliary power transformers that are serving nuclear generating stations. The developed system is capable of detecting such scenario in both unloaded and loaded conditions. The solution lies in the detection of the loss of a single or double-phase in the supply path to power transformers, caused by incorrect switching operation or an unintentionally open or grounded conductor, regardless of the power transformer connection type in the primary and secondary windings, as well as with any type of core.
A typical schematic representation of the system under analysis is shown in Figure 2.

It is considered that the primary currents of the transformer can be measured at the substation, using the current transformers CT_{grid} or near the power transformer (PT) terminals, using current transformers CTPT. It is also considered that a long cable, with capacitance C_{cable}, connects the circuit breaker to the PT.

The estimated open phase detection time is less than five seconds (this is the estimated time to process and analyse all the data acquired by the system).

To perform the open phase detection, the algorithm needs to receive data from three primary voltages and currents of the transformer. As an alternative, the primary currents and the ground current can be measured for fault detection purposes, however, it is recommended to use the primary voltages whenever possible. The diagnostic is achieved by acquiring and processing these electrical variables, providing a clear indication and localization of an open phase scenario. The extremely low current levels can be measured with conventional current transformers, already installed in the substation, with a non-invasive system and without an investment in new measurement devices. The system is able to give, in real-time and remotely, the open phase detection status through an alarm connection for the control room, visual LED indication or a dedicated software.

International organizations that have analysed the problem, recommend monitoring the phenomenon based on measuring the voltage and reverse sequence- and neutral current

The open phase detection algorithm, in each iteration, checks if any other anomalous events exist, before trying to detect open phase faults. Examples of those events are transformer shutdown, grid faults or problems on the load side. If any anomalous condition is detected, the OPD algorithm will be disabled. If all necessary conditions for open phase detection are met, the developed OPD algorithm can work.

The algorithm starts with some pre-processing of the measured currents, given the low amplitude of the signals under analysis when the PT runs at no-load or near no-load. With the resulting information, both the primary currents and the primary voltages are decomposed into three symmetrical components for further analysis. Afterwards, the effects of the cable capacitance need to be compensated (if a long cable is used). This is done with the measured data and with some information collected during the commissioning phase of the diagnostic system.

Once the capacitive effects of the cable are compensated, the developed system calculates the fault indicator (severity factors either for current or power) to evaluate if open phase faults exist. According to the vector group and core type of the PT, a threshold value for the fault indicators (severity factors) is selected with a proprietary algorithm. If the fault indicator is above that threshold, a counter is incremented. When the counter reaches 3, this means an open phase fault was detected. The role of this counter is to increase the robustness of the diagnostic system, so that it does not issue any false alarm, due to, for instance, some event that may disturb the currents drawn by the PT. Once an open phase fault is detected, the signals are further analysed to locate which phase(s) are open circuited. The system finally gives the information to the user about which phase(s) is(are) in open circuit and triggers a digital signal to the outside world so that the maintenance personnel is aware of the PT's faulty condition.

4. Actual Test, Results and Simulations

Field and simulations tests were conducted at Trillo nuclear power plant in the 3rd trimester of 2017, to demonstrate the ability of the EMS OP-TCM system by Enging to detect open phase(s) in a 132 / 10.5 kV three-phase power transformer.

To perform the simulation tests, a proprietary transformer model is used, which enables the simulation of any power transformer. The simulation model takes into account the transformer core geometry and the magnetic circuit properties, allowing one to obtain very realistic results, which include phenomena such as the magnetic saturation and core losses (eddy

Table 1. Main characteristics of current and voltage transformers.

Equipment	Specifications
Current Transformers (132 kV switch yard)	350/5 A, 5P20, 50 VA
Voltage Transformers (132 kV switch yard)	132000/√3-110/√3 V, 100 VA

Open phase conditions can be identified by advanced and state-of-the-art power transformer monitoring systems

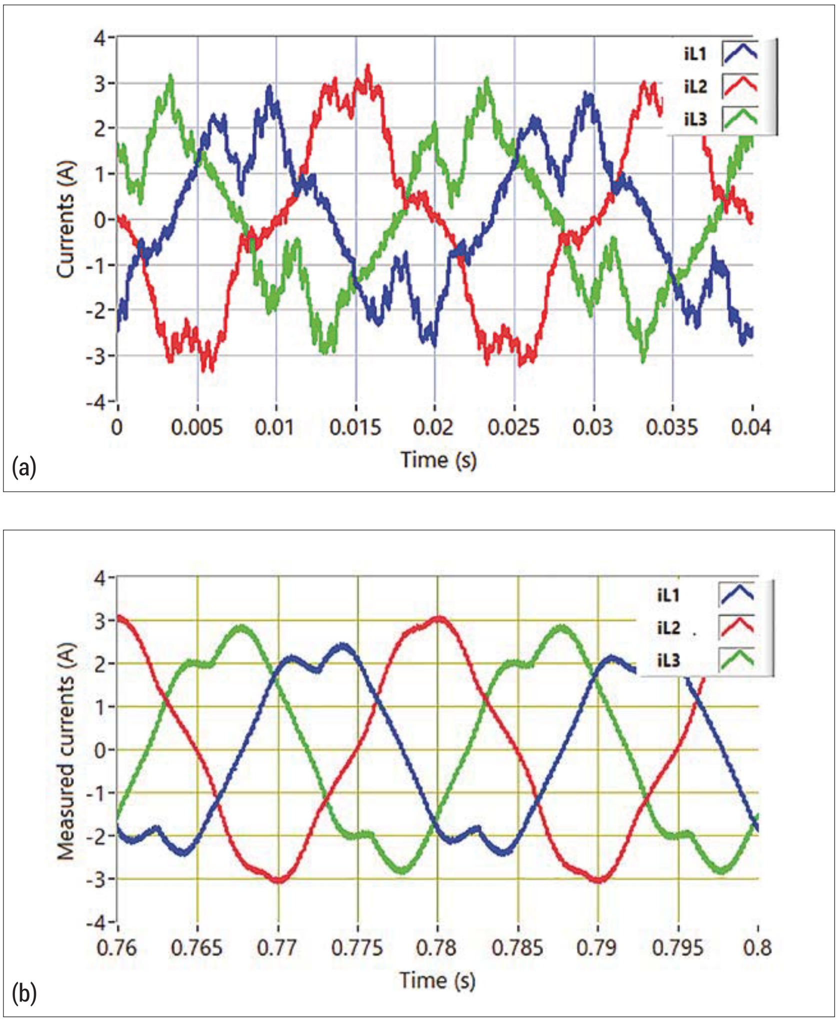

Figure 3. Measured currents with the transformer in normal operation (no-load): (a) Field and (b) Simulation tests.

currents and hysteresis losses). It enables the simulation of any core geometry (core-type and shell-type transformers, autotransformers, phase-shifting transformers and bank of three single-phase transformers), and any number of transformer windings with any type of connection (star, delta, zigzag). The model was developed in Simulink and it can be interfaced with any other power system component (transmission lines, motors, impedances, etc).

The EMS OP-TCM diagnostic system was installed inside a building located in the 132 kV switch yard collecting the information from the current (CT_{grid}) and voltage (V_{L1},V_{L2},V_{L3}) transformers therein available (Table 1). These current and voltage transformers measure the power transformer primary currents and voltages.

The power transformer is located about 470 m away from the 132 kV switch yard, and its supply is ensured by three single pole underground cables with a non-negligible capacitance. The open phase condition was created by closing one or two poles of the circuit breaker installed in the switch yard, leaving the other(s) pole(s) open.

The EMS OP-TCM system was initially commissioned following the recommended procedure:

- With the power transformer switched off (both the high-voltage and medium-voltage sides) the diagnostic system identified the residual noise from all equipment (current transformers installed near the circuit breaker, current sensors of the EMS OP-TCM system itself, etc). This test is performed only once and does not need to be repeated during the system's life time.

- The transformer was then switched on, with the secondary windings disconnected from any load. The on-load tap changer (OLTC) was on tap 7, which is the tap where it stands in normal conditions.

- The diagnostic system then identified the capacitance of the underground cable and remaining equipment that connects the 132 kV busbar to the power transformer. The capacitance estimated by the diagnostic system was 128 nF. This value is in a relatively good agreement with the value measured one year ago (112 nF), which was made available during the tests by the power plant personnel. For the following tests conducted on-site, the capacitance used by the diagnostic system was the estimated value (128 nF) as it is advisable to take into account the inevitable errors introduced by the measurement equipment and also because it is not guaranteed that the cable capacitance is available in all locations where the diagnostic system is to be installed.

- Once these initial tests were performed, the diagnostic system was ready to be used for the detection of open phase conditions.

4.1. Normal Operation

With the power transformer in normal operation, the currents measured by the diagnostic system in the field tests and the simulation ones, are shown in Fig. 3.

The rms values of the three measured currents, the active power per phase and the total active power are shown in Table 2.

The values obtained in the field test are in line with the expected ones for a healthy power transformer. The small differences between the simulation results and the ones recorded in the field

Table 2. Current and active power values during normal operation.

	iL1 (A)	iL2 (A)	iL3 (A)	PL1 (kW)	PL2 (kW)	PL3 (kW)	Ptot (kW)
Field	1.50	1.93	1.51	11.8	9.5	46.2	67.5
Simulation	1.70	2.06	1.90	7.4	19.2	42.4	69.0

Table 3. Severity factors and final result of the EMS OP-TCM system (TP in normal condition).

	Severity Factor for Current (SFi)			Severity Factor for Power (SFp)			Final Result
	Calculated value	Threshold (limit)	Result	Calculated value	Threshold (limit)	Result	
Field	0.28	**0.80**	**Normal**	2.10	**3.00**	**Normal**	Detected OPs L1 L2 L3 ●●●
Simulation	0.22			1.69			

tests, are mainly due to the residual electrical grid unbalance, supply harmonics that exist in practice and that were not considered in the simulation study and also some differences between the magnetic properties of the transformer core in the experiments and the simulated one. Overall, the experiment and simulation results have a good level of correlation, which reinforces the general applicability of the developed diagnostic algorithms.

The values of the severity factors calculated for the current and power signals, which serve as a basis for the diagnostic system to detect open phase conditions, are shown in Table 3. These severity factors are calculated from voltage and current instrument transformers with a proprietary algorithm.

Both severity factors have values below the corresponding threshold limits, meaning that both modules of the diagnostic system indicate that no open phase exists. The results in the field have confirmed what was expected based on the simulation results.

The diagnostic system presented here uses models based on currents and active power, and it can detect open phase conditions from no-load up to rated load in any power transformer

4.2. Open phase in phase L1

With the power transformer with an open phase operation in phase L1, the currents measured by the diagnostic system in the

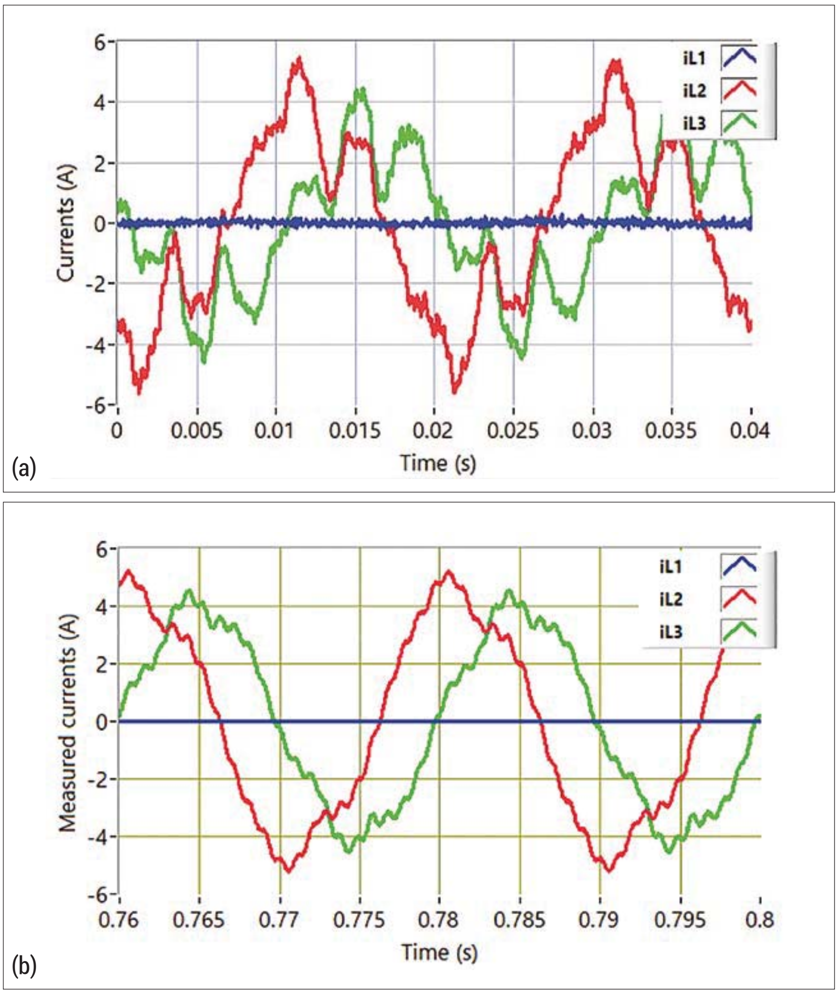

Figure 4. Measured currents with the transformer in L1 open phase operation (no-load): (a) Field and (b) Simulation tests.

Table 4. Current and active power values during L1 open phase operation.

	iL1 (A)	iL2 (A)	iL3 (A)	PL1 (kW)	PL2 (kW)	PL3 (kW)	Ptot (kW)
Field	0.08	2.86	2.25	1.7	104.3	-33.9	72.1
Simulation	0.00	3.33	2.87	0.0	133.2	-64.2	69.0

Table 5. Severity factors and final result of the EMS OP-TCM system (TP in L1 open phase operation condition).

	Severity Factor for Current (SFi)			Severity Factor for Power (SFp)			Final Result
	Calculated value	**Threshold (limit)**	**Result**	**Calculated value**	**Threshold (limit)**	**Result**	
Field	1.05	**0.8**	**Open phase**	6.68	**3.00**	**Open phase**	Detected OPs L1 L2 L3
Simulation	1.03			9.58			

field tests and simulation were the ones shown in Fig. 4.

The rms values of the three measured currents, the active power per phase, and total active power are shown in Table 4.

Once again, the values obtained in the field test are in line with the expected ones based on the simulation study.

The values of the severity factors calculated based on the current and active power signals, which serve as a basis for the diagnostic system to detect open phase conditions, are shown in Table 5.

Both severity factors have values above the corresponding threshold limit, meaning that both diagnostic system modules were able to detect the open phase condition. The final indication of the diagnostic system was that phase L1 was open.

4.3. Open phase in phases L1 and L2

With the power transformer with a double open phase operation in phases L1 and L2, the currents measured by the diagnostic system in the field tests and simulation were the ones shown in Fig. 5.

Described system provides the diagnosis and location of an open phase scenario in less than 5 seconds

The rms values of the three measured currents, the active power per phase, and total active power are shown in Table 6.

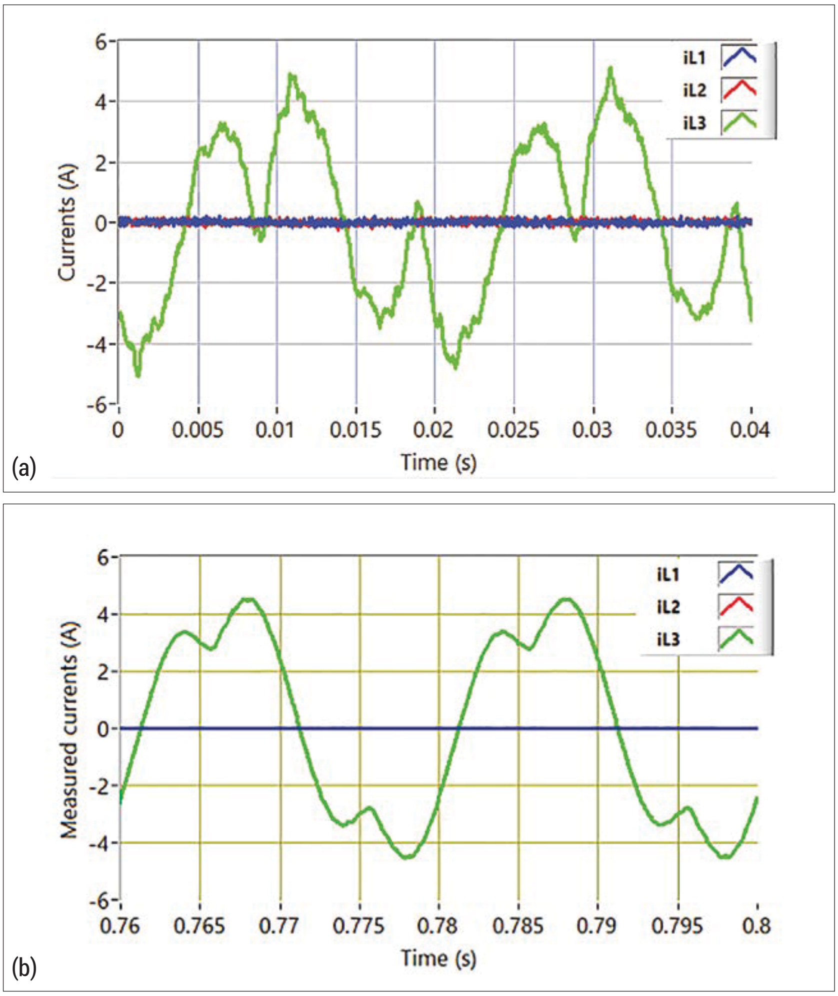

Figure 5. Measured currents with the transformer in L1-L2 open phase operation (no-load): (a) Field and (b) Simulation tests.

Table 6. Current and active power values during L1-L2 open phase operation.

	iL1 (A)	iL2 (A)	iL3 (A)	PL1 (kW)	PL2 (kW)	PL3 (kW)	Ptot (kW)
Field	0.07	0.07	2.68	0.3	0.6	38.8	39.7
Simulation	0.00	0.0	3.12	0.0	0.0	41.6	41.6

Table 7. Severity factors and final result of the EMS OP-TCM system (TP in L1-L2 double open phase operation condition).

	Severity Factor for Current (SFi)			Severity Factor for Power (SFp)			Final Result
	Calculated value	Threshold (limit)	Result	Calculated value	Threshold (limit)	Result	
Field	1.99	**0.8**	**Open phase**	3.86	**3.00**	**Open phase**	Detected OPs L1 L2 L3
Simulation	2.00			4.00			

The values of the severity factors calculated for the current and power signals, which serve as a basis for the diagnostic system to detect open phase conditions, are shown in Table 7.

Both severity factors have values well above the corresponding threshold limits, clearly detecting and locating the double open phase condition in phases L1 and L2.

5. Other Open Phase solutions in the market

Some specific detection systems have been developed for OPC detection even in no loaded transformer situation. Among them:

- Manufacturer 1: system of current injection in the neutral to earth connection. It requires an important modification in the neutral installation of the transformer to be monitored, which can complicate its installation.

- Manufacturer 2: fiber optic current transformer system. It also requires a major intervention in the transformer to be monitored.

- Manufacturer 3: system for monitoring voltages and currents. This system is not suitable for all types and configurations of transformers.

The implementation of this system relies on the use of the standard current and voltage transformers already installed in nuclear power plants

Some utilities of the NPPs in Spain have adopted Enging system as their cost effective solution to detect the open phase condition because it is an non-invasive system and does not require new investments compared to previous systems.

OPC detection systems have become functional very recently; therefore, there is still not much empirical data from the operation, including the insight into their reliability.

Conclusion

Open phase condition is one of the issues that can be solved by advanced and state-of-the-art power transformer monitoring systems. The diagnostic system presented here, which uses detection modules based on currents and active power, is able to detect open phase conditions reliably in any power transformer, in operating condition, ranging from no-load up to rated load. Any type of open phase is detectable, including low and high impedance open phase conditions. The implementation of this system relies on the use of the standard current and voltage transformers already installed in nuclear power plants.

Open phase field test results are reported here, after a successful test at Trillo 1 Nuclear Plant. Up until today, 10 systems have been successfully commissioned by Tecnatom and Enging at Spanish Nuclear Plants Trillo and Almaraz [10], two more are under commissioning, and several others are in bidding process.

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