Keeping a watchful eye on transformers

Partial discharge (PD) measurements with the Power Diagnostix ICM*system* from Megger provide invaluable insights into the nature, location and severity of PD activity and therefore, the associated level of risk. These insights inform asset management decisions fully. In some cases, it may be possible to manage relatively low risk conditions by reducing operational demands on an affected asset until a more convenient outage date is at hand, while in others, immediate repair may be necessary. In either case, the PD measurements provide information about the nature of the repairs required before the repair process is started. This eliminates the need for exploratory investigations to locate the dielectric damage and makes it much easier to prepare for what is likely to be found when the transformer is opened up. This, in turn, leads to better planning, a shorter outage time, lower costs and an improved security of supply.

Figure 1: ICM*system*

PD measurement is a well-established and proven technique for analysing insulation condition in power and large distribution transformers. In fact, for many transformer operators, this technique has become a mandatory element of factory acceptance testing, as well as a key part of their routine maintenance testing program. Power Diagnostix, a Megger company, has been developing PD measuring systems since the 1980s, and this article discusses the applications of one of the company's newest and most versatile products: Power Diagnostix ICM*system*.

After the manufacture of a power transformer has been completed, the core, windings, insulation and other key components, including on-load tap changers, are not easily accessible for inspection and repair. Opening up a transformer to carry out repairs is a difficult, time consuming and costly process. This makes PD testing an invaluable part of the regular maintenance of power transformers since it enables the nature, location and severity of incipient faults to be readily determined.

Dissolved gas analysis

Transformer maintenance typically begins with dissolved gas analysis (DGA), which is a systematic analysis of the transformer oil using a gas chromatograph. There is a wealth of knowledge about how the dissolved gases in transformer oil caused by problems such as overheating, paper ageing and arcing, correlate with the occurrence of PD activity. The initial gas analysis usually focusses on hydrogen, hydrocarbons and carbon oxides such as CH_4, C_2H_2, C_2H_6, CO and CO_2. It provides important preliminary information about the existence of PD activity and its associated risks, but it provides little or no useful information about the location of the PD activity within the transformer. Identifying the location requires two steps: pre-location and pinpointing.

Pre-location of PD activity

The potential or test taps on the high voltage bushings of the power transformer are used to couple the partial discharge signal and facilitate PD measurements. A measuring impedance, known as the PDIX Quadrupole™ is connected to the test tap of each bushing. When combined with a pre-amplifier, each Quadrupole becomes an active high-pass filter that passes high frequency signals. The ICM*system* pre-amplifier has a very high input impedance, which provides an efficient signal transfer that preserves the signal from the transformer on its path through the bushing tap. It amplifies small signals and has a low output impedance (50 Ω), which is ideal to drive the line that connects to the main elements of the ICM*system*. This arrangement allows a good signal-to-noise ratio to be achieved, even over long connections, without the complication of using fibre-optic signal transmission.

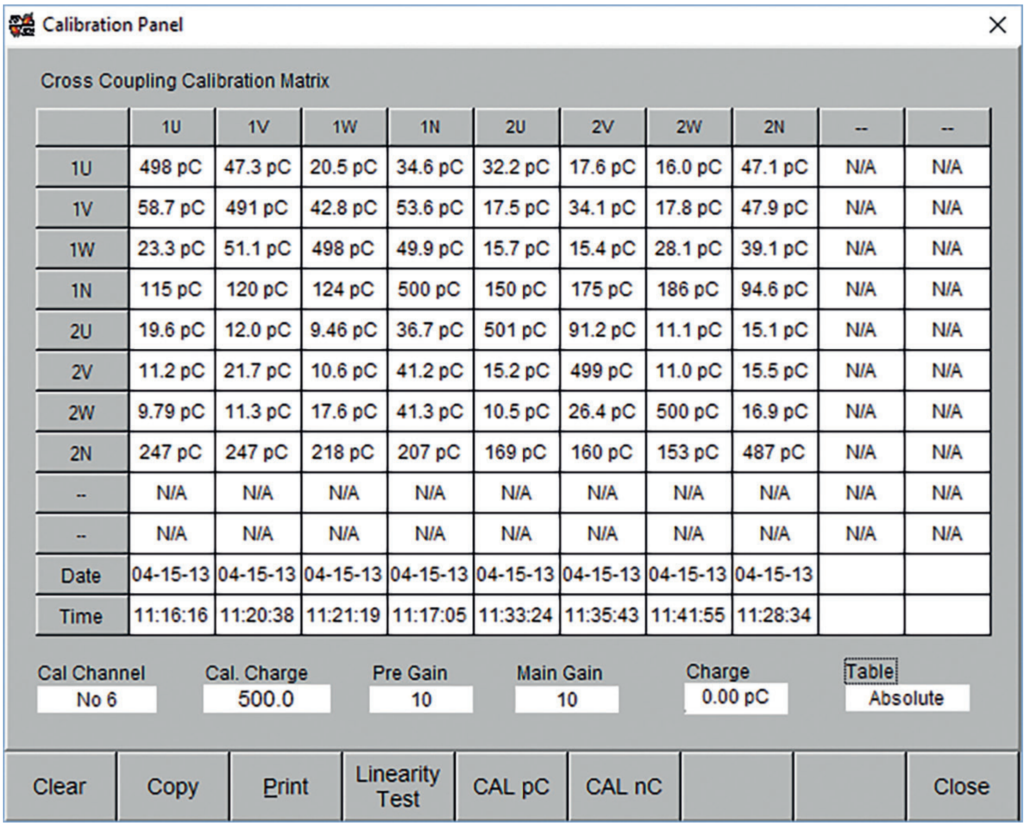
Each test tap on the transformer is assigned to a channel on the measuring device. ICM*system* has ten measuring channels to allow the primary, secondary, tertiary and, if present, the star point, to be measured simultaneously. Once the necessary connections have been made, the measuring system is calibrated by injecting a pulse carrying a known charge into each measured phase. During the calibration process, ICM*system* automatically generates a cross-coupling matrix (Figure 2) which provides information about the coupling of high-frequency signals between the individual measuring points. Comparing the cross-coupling during calibration with the cross-coupling during the PD measurements will give an initial indication of the location of the PD within the transformer.

Pinpointing PD activity

For locating the PD activity more accurately, several options are available.

Variation of excitation mode

The PD inception voltage and the phase position of internal PD activity depend on the mode of the excitation voltage. Varying the excitation mode provides valuable information about the location of the fault in the transformer. In the three-phase induced voltage test, all three phases of the transformer are supplied with high voltage with a 120-degree phase offset. This offset results in further phase shifts in multiples of 30 degrees between winding pairs (e.g. between primary and secondary). This means that a change of the phase position of the phase-resolved PD pattern (PRPD) between single-phase and three-phase excitation provides information about the local electrical field at the fault location and therefore about the location of the fault in the transformer. If the phase position does not change between single-phase and three-phase measurements, the observed fault is



	1U	1V	1W	1N	2U	2V	2W	2N	--	--
1U	498 pC	47.3 pC	20.5 pC	34.6 pC	32.2 pC	17.6 pC	16.0 pC	47.1 pC	N/A	N/A
1V	58.7 pC	491 pC	42.8 pC	53.6 pC	17.5 pC	34.1 pC	17.8 pC	47.9 pC	N/A	N/A
1W	23.3 pC	51.1 pC	498 pC	49.9 pC	15.7 pC	15.4 pC	28.1 pC	39.1 pC	N/A	N/A
1N	115 pC	120 pC	124 pC	500 pC	150 pC	175 pC	186 pC	94.6 pC	N/A	N/A
2U	19.6 pC	12.0 pC	9.46 pC	36.7 pC	501 pC	91.2 pC	11.1 pC	15.1 pC	N/A	N/A
2V	11.2 pC	21.7 pC	10.6 pC	41.2 pC	15.2 pC	499 pC	11.0 pC	15.5 pC	N/A	N/A
2W	9.79 pC	11.3 pC	17.6 pC	41.3 pC	10.5 pC	26.4 pC	500 pC	16.9 pC	N/A	N/A
2N	247 pC	247 pC	218 pC	207 pC	169 pC	160 pC	153 pC	487 pC	N/A	N/A
--	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
--	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Date	04-15-13	04-15-13	04-15-13	04-15-13	04-15-13	04-15-13	04-15-13	04-15-13		
Time	11:16:16	11:20:38	11:21:19	11:17:05	11:33:24	11:35:43	11:41:55	11:28:34		

Figure 2: Cross-coupling matrix during calibration

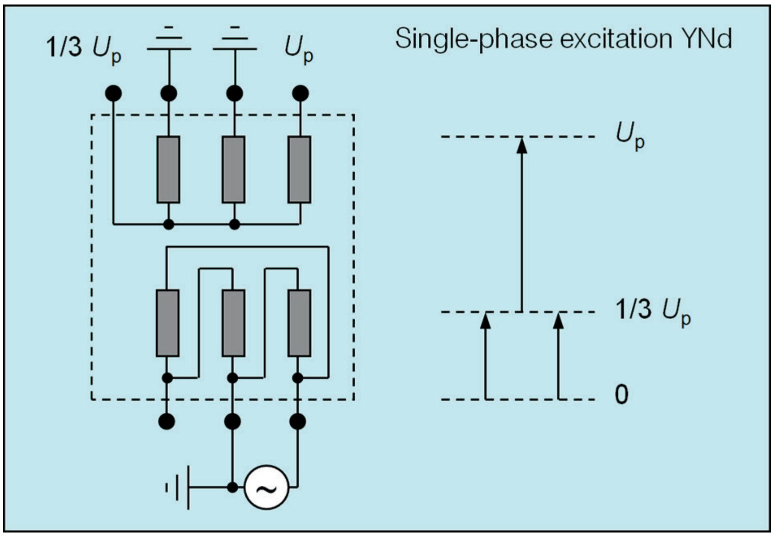


Figure 3: Single-phase excitation on a YNd transformer

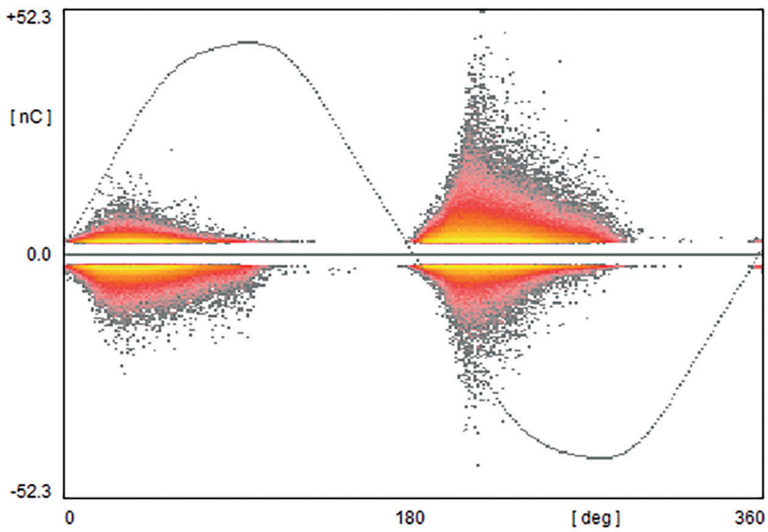


Figure 4: PD pattern for delamination within paper layers

in the phase-earth insulation system, but if the phase position changes, the insulation between two phases is faulty.

Provided that the transformer to be tested permits this operating mode, single-phase excitation with an unearthed star point provides additional diagnostic options. Compared to the usual single-phase induced voltage measurement, the voltage drop within the excited winding is reduced by one-third for excitation with an unearthed star point. As Figure 3 shows, when the star point is unearthed, voltage is distributed across the excited winding in series with the parallel combination of the two other phase windings. The inductive reactance of the parallel combination is one-half of the inductive reactance of the excited winding. Therefore, two-thirds of the voltage drop occurs across the excited winding. Comparing the PD inception voltages between single-phase excitation with an earthed star point and single-phase excitation with an unearthed star point, therefore provides information about the location of the PD fault within the respective winding.

Advanced locating methods enable precise locating

The analytical methods mentioned so far provide information about the fault location within the transformer, without the need for in-depth knowledge of the way in which PD is generated. The following advanced analysis methods can, however, be used to pinpoint the exact fault location down to a few centimetres.

Partial discharge pattern analysis

The appearance of the PRPD pattern is determined by the physical properties of the surrounding insulation medium and the position of the PD source in the insulation medium. There are some typical PD patterns that are often seen in power transformers, and recognising these patterns can contribute toward determining the location of the PD. For example, delamination within paper layers has a very clear PD pattern that allows the areas under suspicion within the transformer to be narrowed down considerably.

Time domain measurement

Partial discharge signals are high-frequency pulses with rise times in the 1 ns range (in air), resulting in frequency components up to 400 MHz. However, power transformers are designed to work efficiently with currents and voltages at 50 or 60 Hz, not at high frequencies. On their way through the transformer, the high-frequency PD signals are inevitably subjected to reflection and oscillation caused by impedance changes, attenuation and dispersion effects. This means that further important information about the location of the PD activity in the transformer can be gained by

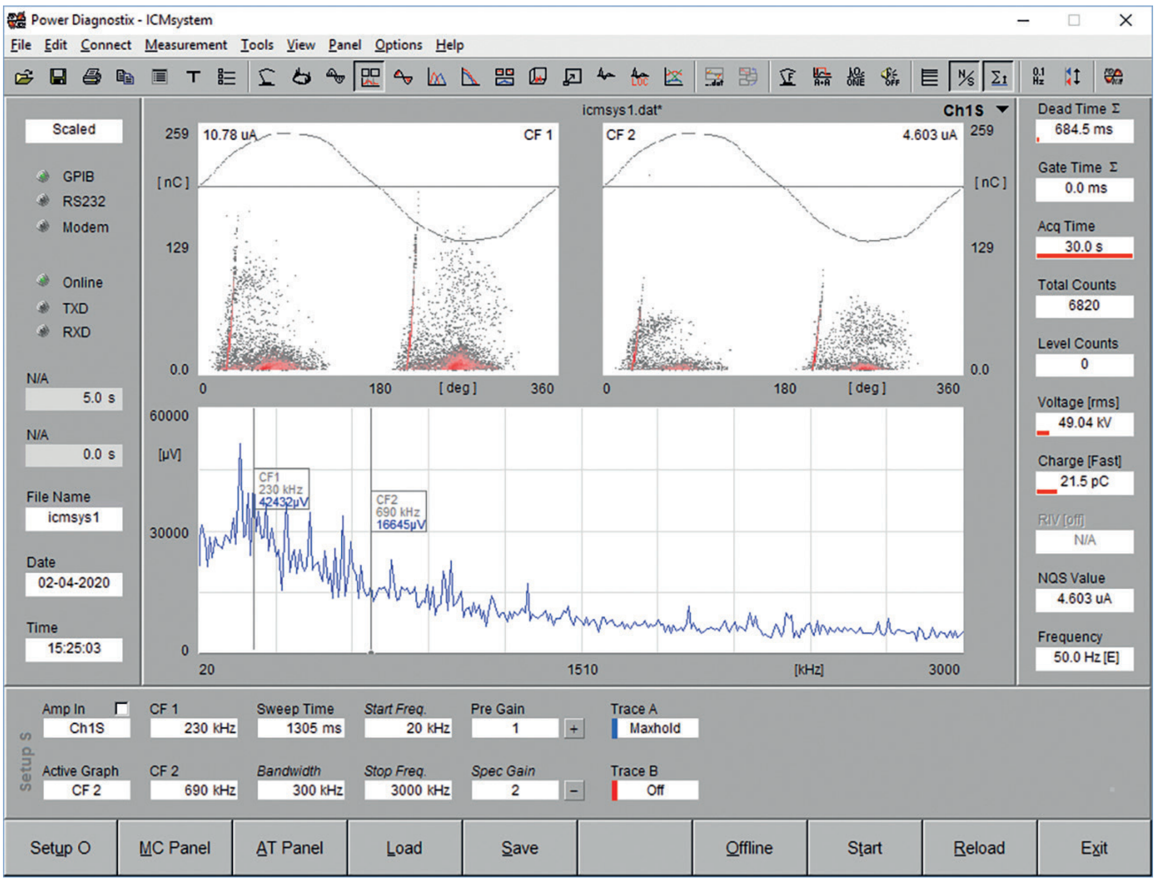


Figure 5: Frequency spectrum

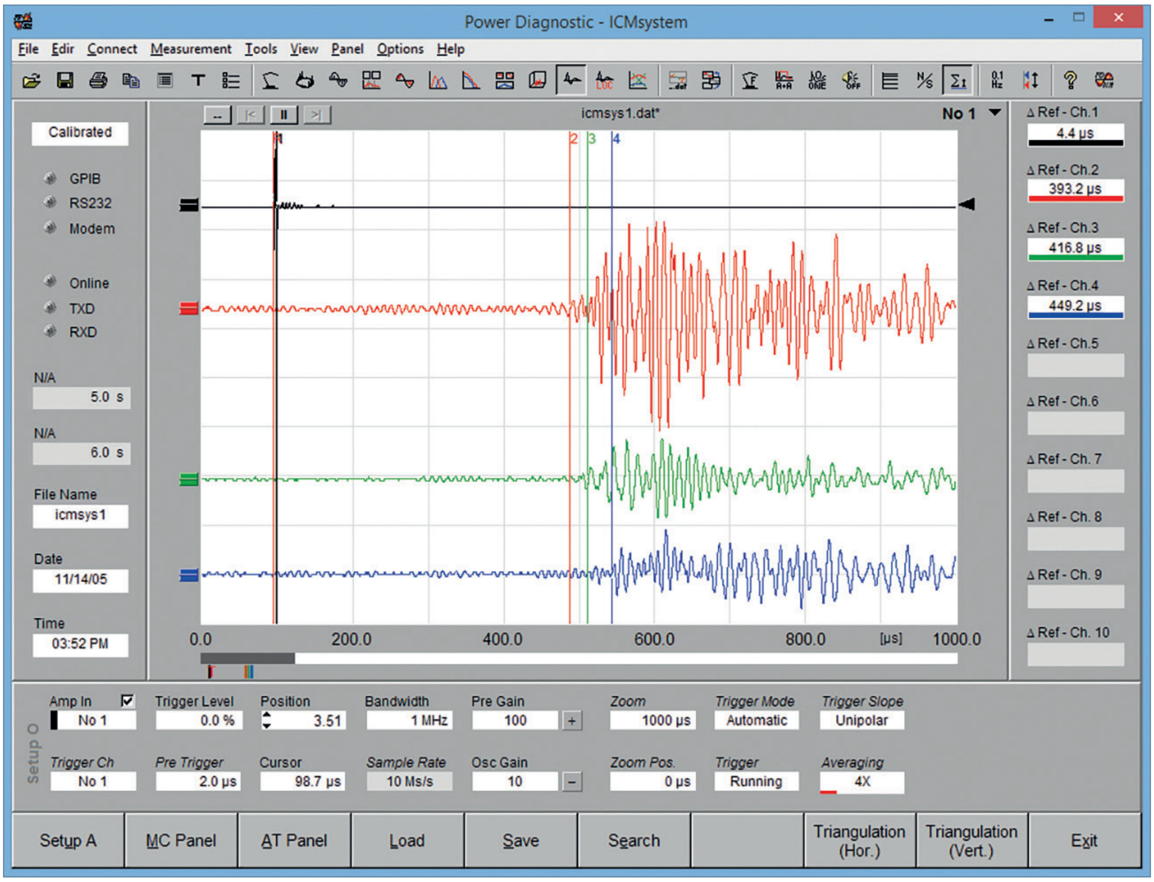


Figure 6: Differences in the delay between the electrical and acoustic signal

comparing radiated and conducted signals using the multi-channel oscilloscope built into the ICMsystem. These signals can be differentiated because conducted signals have less noise and are better defined than radiated signals. When radiated signals predominate, this usually indicates that the PD origin is in a relatively open area, for example, a lead in the transformer tank. In contrast, PD activity buried deep within other components, such as deep inside a winding, produces barely any radiated signals.

Frequency range measurement

A spectrum analyser takes an analogue signal and converts it to a frequency spectrum that provides information about the frequency components making up the signal. In the case of partial discharge, the composition of the frequency spectrum allows conclusions to be drawn about the path the signal has travelled. The ICM*system* can perform a spectrum analysis over the range 10 kHz to 10 MHz. Figure 5 is an example covering the range 20 kHz to 3 MHz. In this case, the signal has only a very small high frequency component, which suggests that it had to travel a considerable distance within the transformer before it was detected by the sensor on the bushing tap.

In contrast, a relatively evenly distributed spectrum would indicate that the location of the PD activity is close to the bushing test tap/measurement point. The complex impedance of the bushing tap itself must also be taken into account. The pulse on the bushing tap is compared with the pulse (on the same bushing tap) that was recorded during calibration. The difference gives precise information about the location of the PD activity.

Acoustic fault detection of PD activity.

In addition to electrical signals, PD activity also produces sound waves at audible frequencies. Piezoelectric sensors on the transformer tank can detect these waves and use them for pinpointing. With the internal multi-channel oscilloscope, the ICM*system* can be used for acoustic fault detection by simply changing the preamplifiers. No expensive additional measuring devices are required.

Compared with electrical signals, acoustic signals propagate relatively slowly at a speed that depends on the medium through which they are travelling. In oil, an acoustic signal has a propagation speed of around 1400 m/s (depending on temperature) while in steel the propagation speed is 5000 m/s or more. Taking this difference into account and using several acoustic

sensors, it is possible to narrow down the location of the fault within the transformer to within a few centimetres by analysing the differences in the delay of the acoustic signals. The biggest difficulty with acoustic fault detection is determining the precise time of origin of the PD pulse. To do this accurately by purely acoustic means, a large number of sensors are needed.

The ICM*system* delivers time and cost benefits

The ICM*system* elegantly bypasses this difficulty by using the electric PD signal decoupled using a measuring impedance at the bushing test tap. This provides a precise reference point, so that only three acoustic sensors are needed to determine the point of origin of the sound waves generated by the partial discharge, and to provide an immediate result. Because of the small number of sensors, the ICM*system* performs acoustic location of PD faults quickly and with little effort, delivering considerable time and cost advantages for users.

In summary, the issue causing PD within the insulation system of a transformer can be quickly and conveniently localised with the ICM*system* to a level of precision that allows accurate repair of the damaged area.

PD measurements on site

In principle, most of the techniques that have been described can be used on site. However, the special circumstances of an on-site measurement must be taken into account. While factory acceptance testing is carried out in specially shielded high voltage laboratories, elevated basic interference levels encountered on-site mean that it is difficult to perform accurate measurements at frequencies below 1 MHz. The optional built-in spectrum analyser of the ICM*system*, therefore, offers the user the ability to perform PD measurements with a variable centre frequency and either a 9 or 300 kHz bandwidth. For on-site measurements, the use of a variable centre frequency maximises the scope for dealing with non-ideal conditions.

The ICM*system* is suitable for both maintenance and factory acceptance testing of power transformers. Combining traditional methods with modern PD measurement technology offers manufacturers and operators of large power transformers an accurate and cost-effective way of obtaining reliable information about the present state of these important and costly assets.

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