

Partial Discharge Measurements on Components Energized by Power Electronic Frequency Converters

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Abstract

The voltage source used for testing electrical equipment has to achieve special requirements, which are noted in the international standards. Still today the test voltages for routine- and type tests of utilities for the power engineering are generated by motor-generator sets. Attempting to replace the m.-g. sets with static frequency converters, two major problems occur in implementing this technology for testing applications: the insufficient quality of the output voltage and the high background noise for partial discharge (pd) measurements. This paper deals with the reasons for the high interference level and the elimination of disturbing emission.

1. Introduction

Nowadays static frequency converters are commonly used in the drive and powertrain technologies, where they, more or less, displace the frequency converters based on motor-generator sets entirely. The classic motor-generator sets (m.-g. sets) are still in use for the test engineering all over the world, generating sinusoidal voltages with frequencies up to 200 Hz. Actual research activities aim to substitute this equipment with static, power semiconductor based, converters providing variable output-frequencies. The main reasons for the replacement of rotating machinery in this area are high investment costs and difficulties in acquisition and transportation. Of course the requirements imposed by international standards still have to be fulfilled satisfactorily.

Implementing this technology two major problems occur: the quality of the output voltage and the partial discharge background noise. Both problems are so extensive that they should not be discussed in one paper. Hence this paper presents the issue of pd measurements being disturbed by frequency converters used as voltage source. A method to obtain a satisfying sinusoidal voltage form can be gleaned in [1].

Good examples for the requirements of the pd-measurements are the conditions demanded for transformer testing. The maximum background noise level of 100 pC for the accompanying measurement during the long duration AC induced voltage test is given in 60076-3 [6]. Special customer requirements can exceed this limit and demand 50 pC or less.

On the other hand, e.g. for testing power cables, a background noise level smaller 1 pC is required.

2. Point of origin

In the beginning a voltage sourced converter fed by a line-commutated rectifier was selected to be the basis for further investigations. The basic principle is shown in Fig. 1.

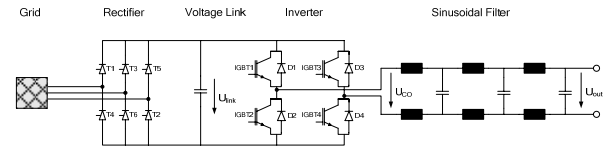


Fig. 1: Simplified equivalent circuit diagram for the voltage sourced converter

The output of the inverter is a pulse width modulated (PWM) signal with maximum amplitude of 540 V. The rising and falling edges are very steep, thus dU/dt is high. The sinus filter smoothes the PWM pattern, and the loads, respectively the test object, are supplied with a sinusoidal 50 Hz voltage. The Total Harmonic Distortion (THD) factor of the output voltage given in (1) is not for all tested loads less than 5 % as demanded in the international standard IEC 60060-1 [8]. Despite this the THD is sufficient to assess the pd interference level.

$$THD = \sqrt{\sum_{k=2}^H u_k^2} \leq 5\% \quad (1)$$

Here $u_k = U_k / U_1$, U_k is the voltage of the kth harmonic and U_1 the voltage of the fundamental component. Frequencies up to the 7th harmonic are considered [6].

To get an initial point the pd test circuit shown in Fig. 2 was build. The output of the converter was connected through an isolating transformer to a test object and a pd test circuit. The first attempt to optimize the system at this point was to put the converter into an EMC-shielded enclosure.

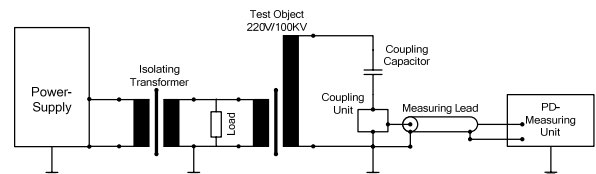


Fig. 2: Simplified equivalent circuit diagram for the pd-test circuit

The results are deflating. Dependent on the link voltage pd levels up to 5000 pC or more are possible. At least factor hundred too high. The peaks on the pd measuring unit are spread over the whole period of the sinusoidal output voltage. The six pulses from the rectifier of the converter are not visible. The IGBT pulses of the H-bridge inverter with their edge steepness dU/dt dominate the performance of the converter concerning pd measurement [2], [3]. Because of the existent parasitic stray capacitances in the test setup the high dU/dt causes pulse shaped interference currents with MHz spectral components in the test setup. Hereby the coupling paths are not predictable [4]. Fig. 3 shows the interference voltage and the inverter output voltage at the output of the coupling unit of the pd measurement equipment.

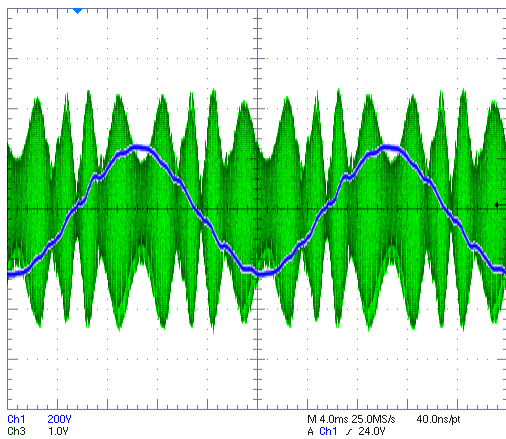


Fig. 3: Output signal and interference voltage at the output of the pd coupling unit over the time.

To avoid a high value of the edge steepness dU/dt , a test with a current link converter was carried out. But the first results then showed a similar behavior. The resultant dI/dt instead of dU/dt did not make any significant changes to the high pd interference level. Hence the further examinations are confined on the voltage sourced converter.

3. Signal paths of the interference signal and screening methods

The signal paths of the interference signals are very diverse. For the pd measurement three main paths are possible: conducted emission, radiated emission and coupling over the earth system. To evaluate the contribution of the different coupling paths to the whole pd background noise, different tests are carried out. The initial test setup is similar to the one shown in Fig. 2.

For the inspection of the radiated emission the connection to the step-up transformer is disconnected, and the following circuit is replaced by an ohmic resistor to load the converter. Table 1 shows the measuring results. After the pd measurement for the radiated emission the setup shown in Fig. 2 is used. The maximum possible voltage in this setup is 225 V. The additional resistor is

inserted to increase the effective load at the converter output. The results for the converter are shown in Table 2.

| S_{out} [kVA] | U_{out} [V] | U_{Link} [V] | Remarks | pd level [pC] |
|--------------------|------------------|-------------------|-------------------|------------------|
| 0,0 | 0,0 | 540 | background noise | 20 |
| 0,0 | 0,0 | 540 | converter no load | 200 |
| 0,37 | 65,0 | 540 | | 700 |
| 1,49 | 130,0 | 540 | | 1200 |
| 4,48 | 225,0 | 540 | | 2000 |

Tab. 1: Pd level caused by radiated emission

| S_{out} [kVA] | $\cos \varphi$ | U_{out} [V] | U_{Link} [V] | Remarks | pd level [pC] |
|--------------------|----------------|------------------|-------------------|-------------------|------------------|
| 0,0 | | 0,0 | 540 | background noise | 20 |
| 0,0 | | 0,0 | 540 | converter no load | 130 |
| 1,10 | 0,55 | 65,0 | 540 | | 1350 |
| 2,55 | 0,6 | 130,0 | 540 | | 2270 |
| 3,74 | 0,6 | 150,0 | 540 | | 2870 |
| 7,84 | 0,6 | 225,0 | 540 | | 4200 |

Tab. 2: Pd level caused by conducted and radiated emission

The separation of the pd noise into radiated and conducted is not well defined, because a pd measurement always shows the maximum value and not a superposition of both. Hence the conducted noise can not be calculated by subtracting the radiated emission level from the conducted and radiated levels. Because of the double pulse resolution time of the pd meter a radiated and a conducted pd pulse can interfere and the absolute value gets falsified.

To inspect the influences of the earth-system on the interference level a separation of the earth system into a “measuring earth” and “power earth” is possible. Naturally the earth system is on earth-potential, but the idea is to separate the measuring equipment comprising pd coupling, measuring unit and the high voltage divider from the power equipment with converter, step-up transformer and EMC shields. Thus a disturbing signal can not directly couple from the source to the pd measuring equipment via the earth system. These changes reduce the pd level, dependent on the output power, up to 500 pC.

The different experiments show, that in this context the emission always propagates by every kind of coupling. Thus the test setup can be improved by different arrangements [5]:

A doubled screened measuring lead from the coupling unit to the pd measuring equipment is one of the most important EMC shields unless the pd measuring system is connected by a fibre optic cable. The second shield is connected with the “power earth” to dissipate the interference.

With the improved setup presented in Fig. 4 the interference level can be reduced to about 50 %. However, a background noise of approx. 2500 pC still exists. To obtain a further reduction it is indispensable to suppress the origin itself.

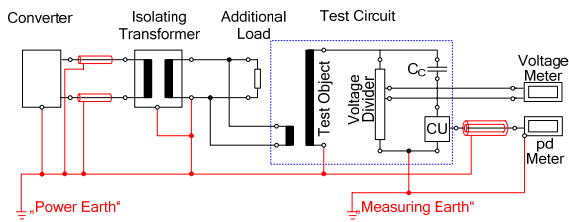


Fig. 4: Simplified equivalent circuit diagram for the pd test circuit.

4. Analysis of the interference signals

As mentioned in chapter 2, the edge steepness dU/dt of the H-bridge converter output is responsible for the high noise level. To prove this statement the converter output (CH 1; 200 V/div) and the input of the pd measuring unit (CH 2; 100 mV/div) are recorded in one diagram, Fig. 5. The oscilloscope shows, that every edge, positive or negative, rising or falling, immediately generates an interference signal at the input of the pd measuring unit. No differences are made between radiated or conducted signals thereby.

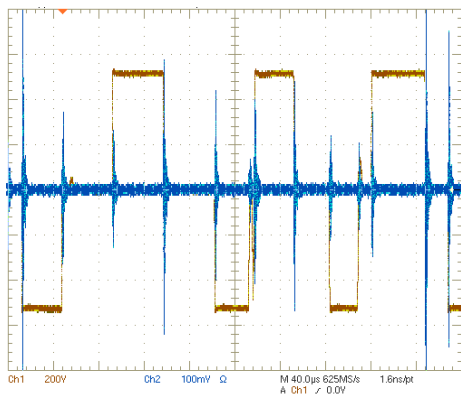


Fig. 5: Converter output and interference signal at the input of the pd measurement device

With a smaller time domain, 1 $\mu\text{s}/\text{div}$ instead of 40 $\mu\text{s}/\text{div}$, a typical interference signal can be observed, shown in Fig 6.

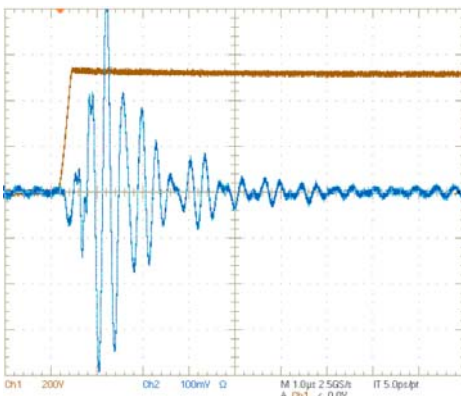


Fig. 6: Interference signal at the input of the pd measurement device

The comparison between the interference signal (Fig. 6) and a 100 pC calibration impulse (Fig. 7) shows an obvious analogy. The recording is oscillating because the calibration impulse is supplied over the test object and recorded at the end of the measuring lead.

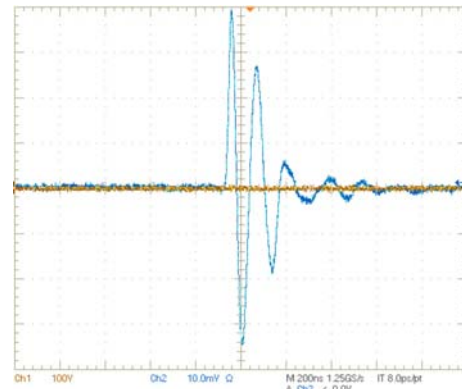


Fig. 7: Pd calibration impulse of 100 pC at the input of the pd measuring unit. Horizontal resolution: 200 ns/div and vertical resolution 10 mV/div.

The oscillation has a higher frequency, but compared with the 100 pC calibration impulse the amplitude of the interference signal is higher by more than factor ten. Consequently an interference level in the range of nC is explainable.

The similarities can also be shown in the frequency spectrum of both signals, which can be calculated using Fourier transformation.

5. Method of resolution

As already shown in chapter 3 it's not possible to reduce the pd level below several thousand pC with the conventional screening methods. The well known gating or windowing is not possible, because there are thousands of pd pulses distributed over the whole phase.

The difference between the real pd signal, reproduced by the calibration impulse, and the interference is too little for a proper application of a filter in the measuring unit. The risk to suppress a real pd signal is too high. Apart from offline diagnosis this problem has only two solutions:

The first and best way to influence all coupling ways at once is, to suppress the interference at the point of origin, the H-bridge inverter. The next possible location to remove the disturbance is at the output of the converter, respectively the adjacent passive sinusoidal filter.

The second approach includes high power band pass filters to filter the conducted noise between the converter and the test object. The radiated coupling can be prevented by running the static frequency converter outside the shielded test laboratory, or inside an EMC shielded enclosure with the high power band pass filter on the barrier between shielded and unshielded surrounding.

5.1. Noise suppression at the inverter output

The interference signal has high frequency components. A common method to cope with RF disturbance is to short circuit these components as proposed in [2], [3], [4]. Special snubber capacitors are impulse voltage stable and have low inductance because of the concentrated design and the special plate connections. Thus they are very capable to feed back the HF to ground and the DC link. Very important is the location and the capacitance of each filter element. Different tests proved the best results for the positions shown in Fig. 7 and a capacitance of 470 nF each.

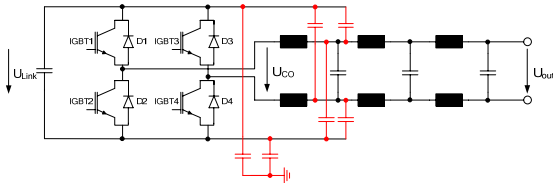


Fig. 8: Conducted and radiated noise suppression filter

These filter elements show a very good performance and reduce the pd background noise up to 80%. Adding the methods described in chapter 3, measurements with a background noise less than 50 pC are possible. To qualify the static frequency converters for replacing the motor generator set entirely the output of the voltage source should be smaller than 1 pC. This can be realized e.g. by power suppression filters.

5.2. High power low-pass filter

The main disadvantage of high power suppression filters is, that the whole output current of the converter must pass the filter elements. Hence this type of filter, which usually is applied to filter the input leads in screened test labs, has a high weight, large dimensions and is very costly. Another disadvantage of this filter is the required transformer for the galvanic separation of the converter output from the filter input.

A high power low pass filter with a maximum current of 60 A_{RMS} was designed to check the fundamental performance of the setup. The filter consists of a feedthrough capacitance and a second order low-pass filter. The 6 dB cut-off frequency is defined to 5 kHz. The properties, attenuation as a function of the frequency, are shown in Fig 9.

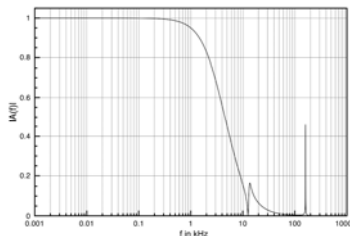


Fig. 9: Filter properties, attenuation over the frequency

Different AC long time induced voltage tests (ACLD) were executed with a separation by open ground between the converter placed outside and the test object

placed inside the screened test lab. During the whole test with voltages up to 45 kV the pd background noise caused by the converter was smaller 1 pC. This demonstrates a total suppression of the disturbance emitted by the static frequency converter.

6. Conclusion

Replacing motor generator sets with frequency converters based on power semiconductors, two major problems occur: The sinusoidal voltage form does not fulfill IEC requirements and the emitted disturbance produces a high background noise for pd measurement of more than 5000 pC.

Starting from conventional screening methods, the pd noise could be decreased to 50 %. For a further reduction full information about the point of origin and the signal itself was necessary. After the switching impulses of the output converter were designated as the source of interference, an assessment of different filter methods was possible.

The analyses of the signals indicated that the noise and the real pd signal are quite similar in the time domain and frequency domain. Consequently, filters in the pd signal paths are not practicable, because the risk to suppress the real partial discharge is too high.

The dissipation of disturbing components at the inverter output with snubber capacitors is the most effective method to reduce the pd level. Measurements with 50 pC or less are possible.

To achieve an absolute interference free pd measurement, a special feedthrough filter was designed to connect voltage source and test object. After the additional separation of power generation and screened test lab by open ground multiple examinations showed an undisturbed pd measurement.

7. References

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