PULSE-SEQUENCE ANALYSIS OF PARTIAL DISCHARGES IN POWER TRANSFORMERS

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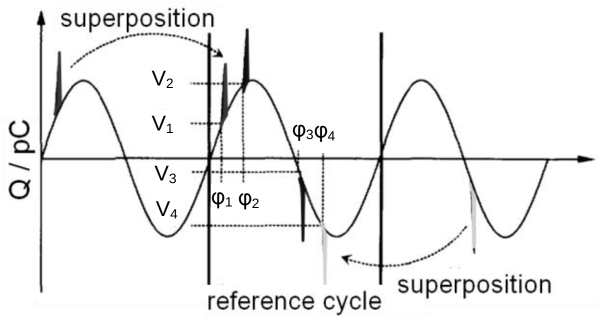
Abstract: Local failures in high voltage insulation systems inside electrical equipment like power transformers may lead to catastrophic breakdowns and can cause high outage and penalty costs. To prevent these destroying events power transformers are e.g. tested on partial discharge (PD) activity before commissioning and in service. A phase resolved partial discharge pattern (PRPD) for the electrical measurements according to IEC 60270 assists to identify the PD type. The PRPD pattern is the most common representation of PDs. Another pattern recognition method is the Pulse Sequence Analysis (PSA). The PSA pattern is created with three consecutive PD impulses assigned to their external test voltage and their phase angle within one period. The PD value of apparent charge in pico Coulomb (pC) is not considered in the PSA. In this contribution different types of PD (void, surface discharge, point-plate, external corona) in mineral oil are investigated regarding their PSA pattern. The PSA patterns of these PD sources show different clusters. So discrimination of different PD types is possible. But multiple PD sources or the amplitude of the test voltage have also a strong influence on the clustering of the PSA pattern. The use of the PSA pattern for a single PD source is a helpful pattern recognition method to describe the PD.

1 INTRODUCTION

Defects in transformer insulation cause partial discharges (PD), which can progressively degrade the insulating material and can possibly lead to electrical breakdown. Therefore, early detection of partial discharges is important. PD measurements can also provide information about the ageing condition of transformers and thus enable conclusions about their lifetime.

The conventional measurement of the apparent charge of PD according to IEC 60270 [1] picks-up signals with a high voltage coupling capacitor. The method is commonly used for quality assurance of high voltage equipment. According to IEC 60270 the measurement setup can be calibrated in terms of pico Coulomb (pC). The measurable apparent charge in terms of pC has no direct relation to the real charge within the PD.

With the electrical PD measurement specific phase-related representations of the electrical measurements (fingerprints) can help to identify the type of fault of the PD source. The PRPD Pattern is the most common representation of PD. In Figure 1 the generation of a PRPD is shown. Therefore the PD events are superposed in one reference cycle [2]. But the correlation between pulses in the same or in different cycles of the applied voltage is not taken into consideration. The parameters of interest here the nominal PD level according to IEC 60270, the level of the test voltage v and the phase of occurrence φ of each discharge. With this information a characteristic pattern occurs.



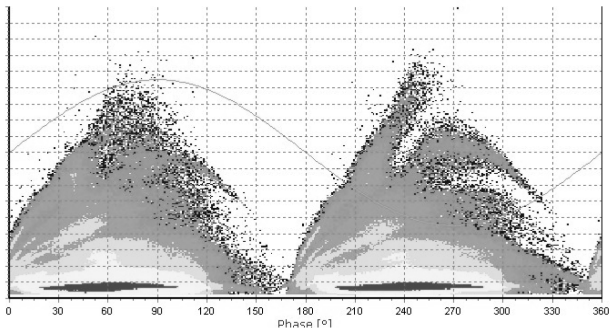


Figure 1: Principle of the generation of the PPRD Pattern, PRPD pattern of a surface discharge

Another pattern recognition method is the Pulse Sequence Analysis (PSA). The PSA was already investigated in solid insulation materials [3]. Therefore the sequences of three consecutive PD pulses are used to generate the PSA pattern.

2 PULSE SEQUENCE ANALYSIS

The PSA pattern is created with three PD impulses related to their external test voltage and their phase angle within one period. The PD level in terms of pC is not considered in the PSA. In Figure 2 the PSA is shown schematically. Therefore, the three impulses PD_{n-1}, PD_n and PD_{n+1} with their voltage values v_{n-1}, v_n, v_{n+1} and the phasing φ_{n-1}, φ_n, φ_{n+1} are considered for the PSA pattern.

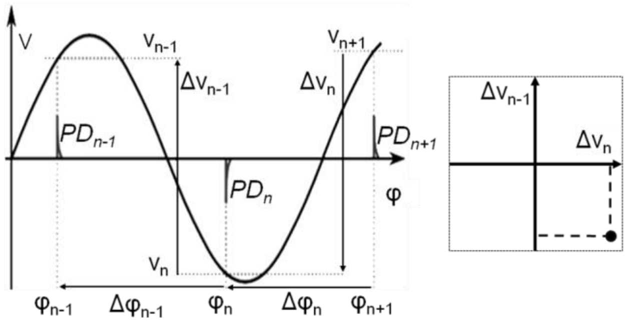


Figure 2: Principle of the generation of the PSA Pattern

The differences for the $\Delta v_n / \Delta v_{n-1}$ or rather $\Delta\varphi_n / \Delta\varphi_{n-1}$ patterns are calculated according to equations (1) (2) (3) and (4). The voltage gradient patterns m_n / m_{n-1}, equations (5) and (6), are also considered for the PSA. The voltage is normalised with the peak value of the test voltage.

$$\Delta v_n = v_{n+1} - v_n \tag{1}$$

$$\Delta v_{n-1} = v_n - v_{n-1} \tag{2}$$

$$\Delta\varphi_n = \varphi_{n+1} - \varphi_n \tag{3}$$

$$\Delta\varphi_{n-1} = \varphi_n - \varphi_{n-1} \tag{4}$$

$$m_n = \frac{\Delta u_n}{\Delta\varphi_n} \tag{5}$$

$$m_{n-1} = \frac{\Delta u_{n-1}}{\Delta\varphi_{n-1}} \tag{6}$$

where: V = Voltage in Volt (V)
φ = phase angle (°)

PSA patterns of different PD fault types are visualised as plots seen in Figure 2. The values of the differences Δv_n, $\Delta\varphi_n$ and m_n are plotted to the ordinate and the Δv_{n-1}, $\Delta\varphi_{n-1}$ and m_{n-1} to the abscissa. The measurements were performed with the measuring setup of IEC 60270 with coupling capacitor, quadrupole and a measurement device. In this case a 2.5 GS/s oscilloscope were used to get the data of voltage and phase of the PD events.

3 RESULTS

Each PD fault has different characteristic local field changes that lead to the ignition of a partial discharge. Since the chosen analysis parameters Δv and $\Delta\varphi$, thus the gradient m, depending on these parameters, typical pattern for different PD sources are expected. The representation in a PSA pattern is the ability to physically identify these effective mechanisms of the PD behaviour. The PSA should be suitable for a PD pattern recognition or rather identification of the PD source.

The PSA of different PD sources form different cluster in all three PSA plot types. In this paper four different PD sources, corona in air (a), void (b), surface discharge (c) and internal corona (d), were compared with each other.

3.1 PSA Pattern of Voltage Differences

In Figure 3 the PSA of the voltage differences $\Delta v_n / \Delta v_{n-1}$ of all four PD sources are shown. Because of the normalised voltage values all data points are in the range of $-2 < \Delta v < 2$. The PSA of a corona in air (a) forms one cluster in the middle of the pattern. The seven clusters of the void and the internal corona are located on the edges, the axis and the mid of the pattern, see Figure 3 b) and d). The internal corona clusters scatters whereas the data points of the void clusters are close together. The surface discharge forms five clusters; four of them on the axis and one in the middle of the pattern. The cluster in the centre of the patterns occurs when the PD signals appear consecutively.

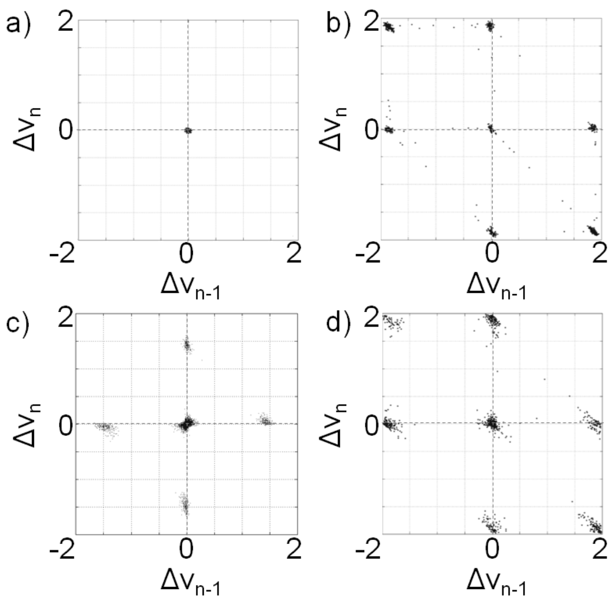


Figure 3: PSA Pattern $\Delta v_n / \Delta v_{n-1}$ of a) corona, b) void, c) surface discharge and d) internal corona

3.2 PSA Pattern of Phase Differences

In Figure 4 the PSA of the phase differences $\Delta\varphi_n / \Delta\varphi_{n-1}$ of all four PD sources are shown. All data points of the pattern are in the range of $-360° < \Delta\varphi < 360°$. The PSA of a corona in air (a) is located in the middle of the PSA and is comparable to result of the $\Delta v_n / \Delta v_{n-1}$ Pattern. Clusters of the void and the internal corona form seven clusters on almost the same position in the plots, see Figure 4 b) and d). Comparing these patterns with the $\Delta v_n / \Delta v_{n-1}$ pattern they look similar. Also the internal corona clusters scatters more than the void clusters. The surface discharge forms five clusters but the positions of the clusters differ to the $\Delta v_n / \Delta v_{n-1}$ pattern.

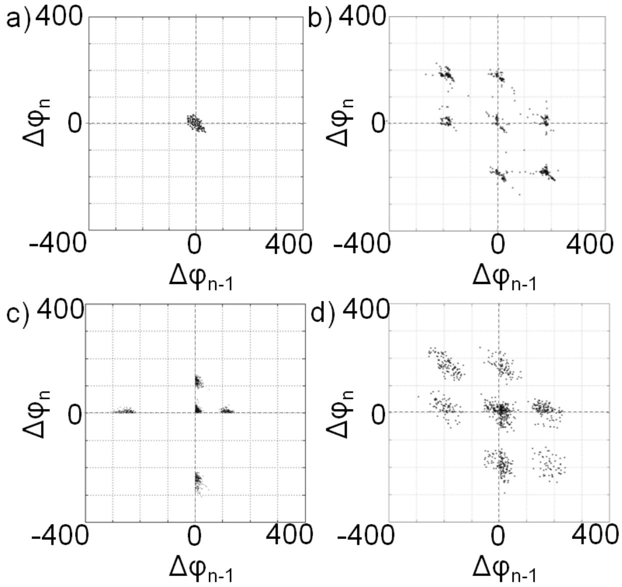


Figure 4: PSA Pattern $\Delta\varphi_n / \Delta\varphi_{n-1}$ of a) corona, b) void, c) surface discharge and d) internal corona

The internal corona and the void showed similar results. Therefore the gradient of voltage and phase m_n / m_{n-1} has to be taken into account.

3.3 PSA Pattern of Voltage Gradient

In Figure 5 the PSA patterns of the voltage gradient are shown.

The cluster of the gradient m_n / m_{n-1} of the corona in air is still located in the middle of the pattern, see Figure 5 a). The void b) and the internal corona d) form totally different clusters. The void generates clusters in lines and the internal corona four clusters which scatter. The surface discharge also forms four clusters but the positions compared to the internal corona are different.

In summary all three PSA pattern, $\Delta v_n / \Delta v_{n-1}$, $\Delta\varphi_n / \Delta\varphi_{n-1}$ and m_n / m_{n-1}, showed differences in the patterns, see Figure 3, 4 and 5. The patterns of the void and the internal corona are similar but the gradient showed considerable differences.

Therefore the PSA can be used to distinguish between the investigated PD sources. For further investigations the voltage differences and the gradient were used to compare the results.

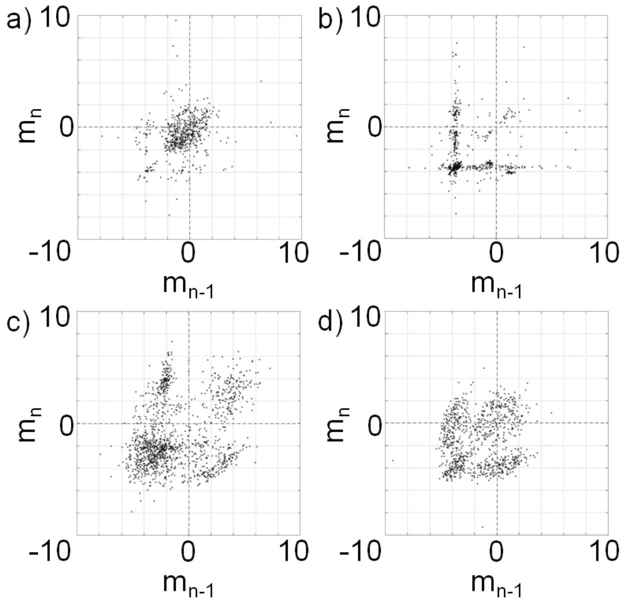


Figure 5: PSA Pattern m_n / m_{n-1} of a) corona, b) void, c) surface discharge and d) internal corona

3.4 Influence of the Applied Voltage

The PSA depends on the PD activity and though on the applied test voltage. If the applied voltage is higher than the partial discharge inception voltage the PD activity is significantly higher. In Figure 6 the influence of the PSA of a void with two test voltages are shown.

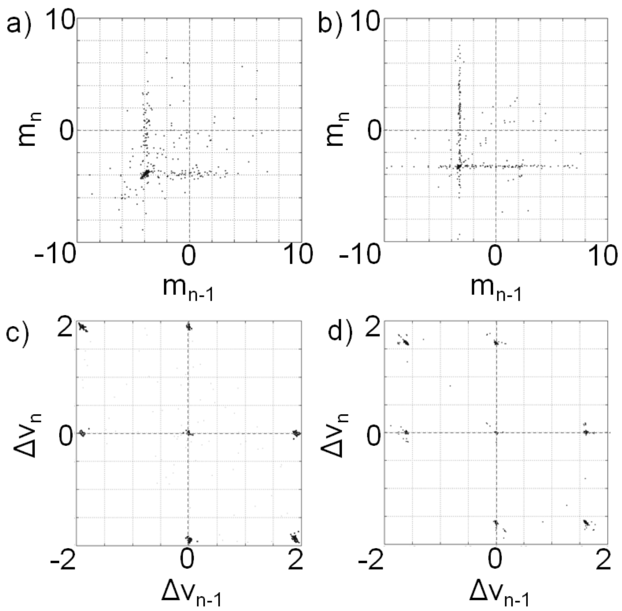


Figure 6: PSA Pattern m_n / m_{n-1} and $\Delta v_n / \Delta v_{n-1}$ of a void with different test voltages; a) and c) $1.4{*}V_{in}$; b) and d) $1.75{*}V_{in}$

The PSA patterns of Figure 6 a) and c) are comparable with the results of Figure 3 b) and 5 b) and the voltage was 1.4 times higher than the inception voltage. In Figure 6 b) and d) the voltage was even 1.7 times higher. The PSA clusters of the higher test voltage shift closer to the centre of the pattern, e.g. ($\Delta v_n|\Delta v_{n-1}$) (2|-2) shifted to (1.6|-1.6). The same effect can be seen for the gradient m_n / m_{n-1} where the lines are also shifted to the middle.

4 INFLUENCES ON THE PSA PATTERN

Interferences affect the PD pattern during a measurement. Noise or periodic disturbances can change the PSA patterns. In transport and distribution networks three-phase transformers are used. Cross-talk between the phases or multiple PD sources can also make the identification of the PSA pattern difficult. A three phase test setup offers the possibility to test the influence of noise, multiple PD sources and cross-talk of one phase to another.

The PRPD of a measurement of an internal corona is shown in Figure 7 a). The PSA patterns without noise are comparable to the results of Figure 3, 4 and 5 d). Figure 7 b) shows the PRPD of the same PD measurement with noise. The PSA patterns $\Delta v_n / \Delta v_{n-1}$ and $\Delta\varphi_n / \Delta\varphi_{n-1}$ forms complete different clusters, see Figure 7 c) and d). The PSA patterns cannot be used to indicate an internal corona or any other typical pattern reached in Chapter 3. That means that the PSA measurement has to be done upon the noise level otherwise no result can be reached. PD smaller than the noise level are considered neither in the PSA nor in the PRPD pattern. A PRPD pattern with noise can be interpreted because the PD level in terms of pC is still considered.

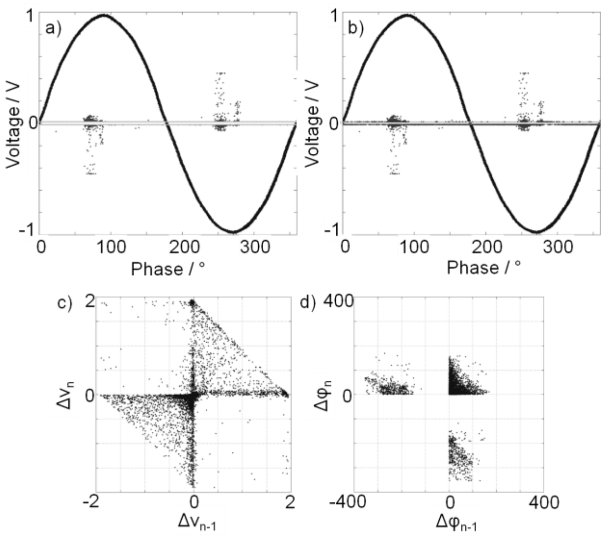


Figure 7: PSA Pattern of an internal corona with noise; a) PRPD without noise, b) PRPD with noise, c) and d) $\Delta v_n / \Delta v_{n-1}$ and $\Delta\varphi_n / \Delta\varphi_{n-1}$ of PRPD b)

For a measurement with a PD source on one phase, e.g. L_3 and a measurement device on phase L_1 impulses can be measured because of the cross-talk and stray capacitances and impedances of the measurement setup. The values of the coupled impulses of the void placed on phase L_1 are less than the impulses on the phase L_3. The phasing and the voltage of the PD impulses of phase L_3 are 240° shifted to the measuring phase. Therefore a change of the PSA is expected.

In Figure 8 the result of the measurement on phase L_1 is shown. The PSA of the gradient voltage m_n / m_{n-1} shows similarities to the PSA of the results in Figure 5 b). But the clusters scatter and the cluster in ($m_n | m_{n-1}$) (4-8|4-8) cannot be seen in Figure 5 b). The PSA voltage difference pattern forms more than seven clusters and scatter. The PD source cannot clear defined as a void. The measured coupled PD impulses change the PSA pattern and the identification of the PD source is not possible.

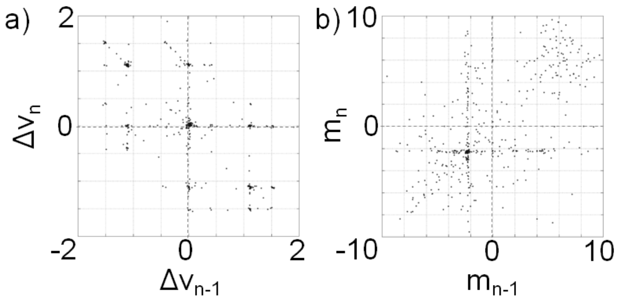


Figure 8: PSA pattern of phase L_1 with PD source (void) on L_3; a) $\Delta v_n / \Delta v_{n-1}$ and b) m_n / m_{n-1}

The influences of multiple PD sources on the PSA pattern need to be investigated as well. By onsite measurements on older power transformers mostly more than one PD source can be detected. The influence of the noise and the coupled impulses of other phases suggest that multiple PD sources will change the PSA pattern as well.

In Figure 9 the result of the measurement with two PD sources on different phases is shown. Therefore the first PD source, void, is located on phase L_1 and on phase L_3 an internal corona PD source was placed. The measurement was recorded on phase L_1.

The PSA voltage difference pattern $\Delta v_n / \Delta v_{n-1}$ forms seven clusters but also lines occur which connect the clusters. The PSA of the gradient voltage m_n / m_{n-1} shows similarities to the PSA of the results in Figure 5 b). The data points between the lines ($m_n | m_{n-1}$) (-4 to 4|-4 to 4) cannot be seen in Figure 5 b). The voltage gradient pattern m_n / m_{n-1} in Figure 9 b) looks like a combination of the PSA patterns of Figure 5 b) and d). But the PD sources cannot be identified clearly.

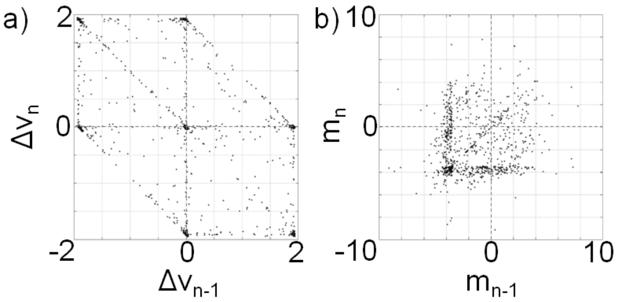


Figure 9: PSA pattern of phase L_1 with void on phase L_1 and internal corona on Phase L3 a) Δv_n / Δv_{n-1} and b) m_n / m_{n-1}

Also the corona in are typical disturbances for onsite measurements. In Figure 10 the PSA pattern of the measurement of a corona in air and a void are shown. The PSA of the gradient voltage m_n / m_{n-1} shows similarities to the PSA of the results in Figure 5 a) of the corona in air. That means that the impulses of the corona are determining the pattern because the typical void clusters disappear. The PSA $\Delta v_n / \Delta v_{n-1}$ form four clusters in the middle of the pattern. Also small clusters can be seen on (Δv_n / Δv_{n-1}) at (-1.5|2), (2|0) and (0|-1.5). The PD source cannot clearly be characterized as a void or a corona in air.

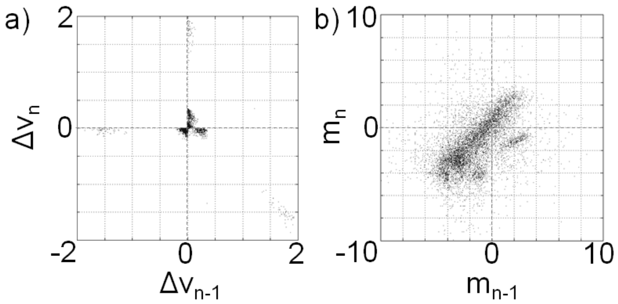


Figure 10: PSA pattern of phase L_1 with void on phase L_1 and external corona; a) Δv_n / Δv_{n-1} and b) m_n / m_{n-1}

In summary the PSA is a pattern recognition method which is highly susceptible for disturbances. Multiple PD sources or external PD changes the PSA pattern. The influences, shown in chapter 4, confirmed that the PSA method needs higher measurement accuracy than the PRPD pattern. Noise disturbs the PSA pattern whereas a PRPD can be still interpreted.

The different PD sources and noise should be distinguished to get the PSA of a single PD source Maybe the STAR diagram [4] could be used.

5 CONCLUSION

Pulse Sequence Analysis is a PD pattern recognition method which was originally investigated in solid insulation materials. For paper/oil insulations the results showed differences of the typical PD sources void, surface discharge and internal corona. Also the PSA of corona in air as disturber for onsite measurements was investigated. In all three PSA pattern $\Delta v_n / \Delta v_{n-1}$, $\Delta\varphi_n / \Delta\varphi_{n-1}$ and m_n / m_{n-1} differences can be seen and so every PD source can be described with its typical PSA pattern, see Figure 3, 4, and 5.

The test voltage has an influence on the PD activity and so consequences on the PSA pattern. In Figure 6 the pattern at two different voltages are shown. The numbers of clusters are the same but the clusters are shifted in the pattern. But the identification of the type of PD is still possible.

Multiple PD sources, cross-talk of PD sources and noise changed the PSA tremendously. Identification of the PD type is not possible anymore. For multi-terminal PD measurements the STAR diagram [4] could be helpful to distinguish between multiple PD sources or external noise (corona in air).

The PSA is a helpful pattern recognition method for single PD sources. The PRPD pattern is still preferable because of the information of voltage, PD level and phase. For difficult cases a PSA pattern can be an additional method to describe the PD source.

6 REFERENCES

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