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Design Parameter Based Method of Partial Discharge Detection and Location in Power Transformers

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Abstract: Insulation defect detection in time ensures higher operational reliability of power system assets. Power transformers are the most critical unit of power systems both from economical and operational front. Hence it becomes necessary to have knowledge of the actual insulation condition of transformer to increase dependability of the system. The performance and ageing of the transformer insulation is mainly affected by Partial discharges (PD). Proper diagnosis in terms of amplitude and location of partial discharge in a power transformer enables us to predict well in advance, with much confidence, the defect in insulation system, which avoids large catastrophic failures.

In this work a 20kVA, 230/50kV single phase core type transformer is used for evaluation of the transfer function-based partial discharge detection and location using modeling of the winding, using design data. The simulation of capturing on-line PD pulses across the bushing tap capacitor is done for various tap positions. Standard PD source model is used to inject PD pulse signal at 10 tap locations in the winding and corresponding response signatures are captured at the bushing tap end (across 1000pF). The equivalent high frequency model of the winding is derived from the design parameters using analytical calculations and simulations in packages such as MAGNET and ANSOFT. The test conditions are simulated using ORCAD-9 and the results are evaluated for location accuracy using design parameter based PD monitoring method.

Keywords: Power transformers, Partial discharge detection, Insulation defect detection, Design parameters.

1 Introduction

Partial discharges (PD) are localized electrical breakdowns within the insulation, which do not bridge the end electrodes. During the occurrence of PD, energy dissipation takes place and can be attributed to various kinds of generated signals such as electrical current pulses through earth, voltage drop across electrodes, electromagnetic radiations, optical signal and acoustic energy

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emission simultaneously. Furthermore, PD is also attributed to post effect which is reflected in chemical property of insulation oil (Dissolved Gas Analysis). PD measurements can be conducted either continuously or intermittently, on-line or off-line. PD results are a reliable source to assess the health of electrical equipment and to plan for maintenance.

Acoustic Emission (AE) PD detection method is based on the fact that partial discharges produce acoustic waves in a frequency range up to 150 kHz within the transformer tank [1]. Special piezo-electric sensors are placed on the outer surface of the transformer tank in order to detect these waves that propagate from the PD source to tank through dielectric medium. AE method is usually sensitive to PD level of above 500pC [2]. The optical method uses multiple fibre optic cables placed at various PD prone locations, which increases complexity and decreases reliability. Ultra high frequency (UHF) PD detection method detects radiated electromagnetic waves in the frequency range of 0.3–3GHz for detecting discharges in power transformers [3, 4, 5]. A major difficulty of this method is the suppression of noise and external disturbances that are similar to the PD signal, which affect the accuracy and sensitivity of detection [18].

Electrical PD detection methods are classified as conventional off-line methods [2], which measure apparent charge quantity using conventional PD measuring circuitry and instruments with a centre frequency of 500kHz and 250kHz for narrowband method and wideband methods respectively [10]. PD type and location can be determined by analyzing the shape of the captured PD signal in time domain. The other electrical method, which is preferable for on-line monitoring, captures the earth current and bushing current signals propagated along the winding height. Recent developments in electrical methods are based on the fact that while a discharge signal propagates from the location to the measuring terminals, the terminal response acquires the information on the location of the PD source. The PD type and location can be determined by frequency spectrum analysis of the captured signal.

2 Theoretical Background

Considering the mathematical model of a single layer transformer winding shown in Fig. 1, high frequencies in the measurement are due to the capacitance present between transformer windings and earthed parts (core, tank, etc.), within each winding, between discs, turns and layers, and between individual coils. Owing to this capacitance the voltage distribution of steep-front over voltages within the transformer will not be uniform [19, 21]. A section of the model two of its element, each of its length $\mathrm{d}x$, the inductance of each element is denoted by L [H/m], its shunt capacitance by C_g [F/m], and its series capacitance by C_s [F/m]. The equivalent circuit is as shown in Fig. 1.

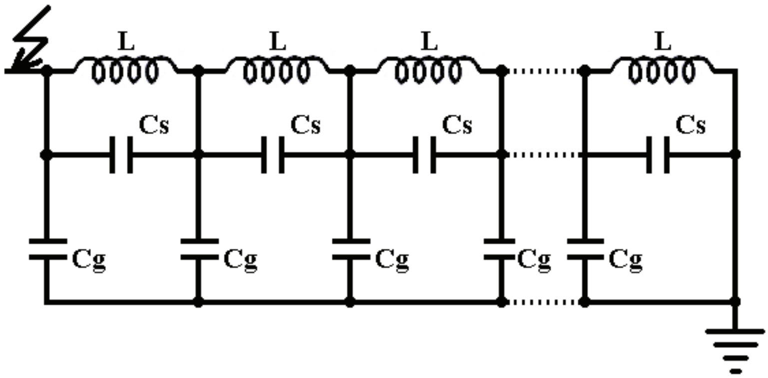


Fig. 1 – *Mathematical model of a single layer transformer winding at high frequencies.*

In the low frequency range, the signal travels through the equivalent transmission line of the winding with a finite propagation velocity. The time delay between the two terminal signals depends on the position of the PD source relative to the terminals. This time delay can be used for location and such a technique is called the travelling wave method. In the higher frequency range, the capacitive ladder network applies. The ratio of the two terminal signal magnitudes can be used for location. This is called the capacitive ratio method. From the previous works on the PD location using the series resonant frequencies the equation is given as:

$$x_0 = 1 - \frac{n}{2f}\sqrt{\frac{1-4\pi^2 f^2 LC_s}{LC_g}}\,, \tag{1}$$

where:

x_0 – location PD along the winding height (p.u.);

n – order of series resonant frequency considered;

f – value of the series resonant frequency [Hz].

Equation (1) can be used to calculate the location of the PD source when the frequency of a series resonance of the line-end discharge signal (*f*) and its order (*n*) is known, provided that LC_g and LC_s values of the equivalent circuit of winding are also known. Equations (2) and (3) shows that if two series resonances f_1 and f_2 can be obtained corresponding to n_1 and n_2, then LC and LK can be found for the equivalent circuit of the winding and are given by

$$LC_g = \frac{(n_1 n_2)^2}{4\left(n_2^2 - n_1^2\right)}\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right), \tag{2}$$

$$LC_s = \frac{1}{4\pi^2\left(n_2^2 - n_1^2\right)}\left[\left(\frac{n_2}{f_2}\right)^2 - \left(\frac{n_1}{f_1}\right)^2\right]. \tag{3}$$

3 Performed Work

In this work a 20kVA, 230V/50kV, transformer was designed for the experimentation with 10 accessible taps on the HV to facilitate injection of PD across the winding height. The design parameters are as follows:

LV winding:

Type of winding: Layer

No. of layers: 2

Total No. of turns: 92

No. of turns / layer: 46

Insulation between turn = 0.4mm

Inner Diameter: 119mm

Outer Diameter: 145mm

Electrostatic shield (copper foil):

Inner Diameter: 210mm

Outer Diameter: 211mm

HV winding:

Type of winding: Crossover coils

No. of crossover coils: 10

No. of turns / coil: 2000

No. of Layer / coil: 53

No. of Turns / Layer: 38

Inner Diameter: 212mm

Outer Diameter: 288mm

Since only the HV winding is subjected to PD and corresponding measurements are done on this winding we shall focus on the design and simulation of HV winding. The high frequency model of the HV winding is derived from the design data using conventional [26] analytical calculation method and the parameters series capacitance, shunt capacitance [19], self inductances and mutual inductances [21][22] were calculated. Simulation packages such as MAGNET and ANSOFT also used to derive named parameters. The equivalent circuits (calculation result and simulation results) are simulated for the test condition i.e., PD signals are injected at various tap positions and corresponding bushing end current signals are captured for analysis the snapshot of the simulation is as shown in Fig. 3. The accuracy of the location algorithm in term of percentage height of winding is evaluated and compared.

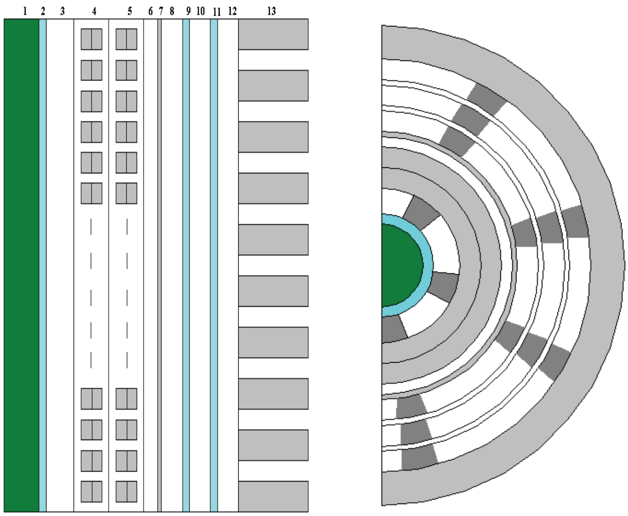


Fig. 2 – *Plan and elevation of the construction of windings.*

1 - Core
2 - PCB wrap
3 - Oil duct
4 - LV layer 1
5 - LV layer 2
6 - PCB wrap
7 - Copper foil (Electrostatic shield)
8 - Oil duct
9 - PCB wrap
10 - Oil duct
11 - PCB wrap
12 - Oil duct
13 - HV crossover coils

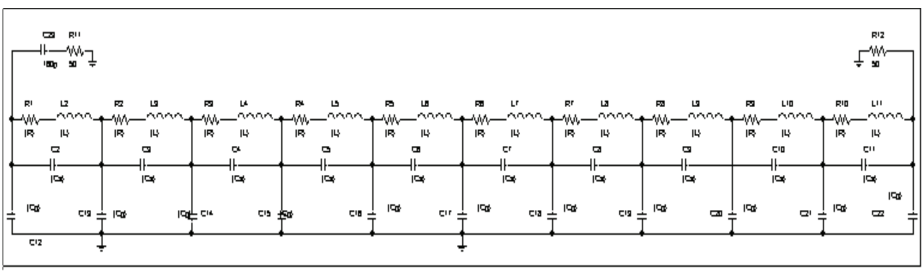


Fig. 3 – *Snapshot of the simulation of* 10 *section circuit.*

A bushing capacitor of 1000pF is used for simulation. Conventional capacitor model with 5ns pulse width is given as the PD signal as shown in Fig. 4.

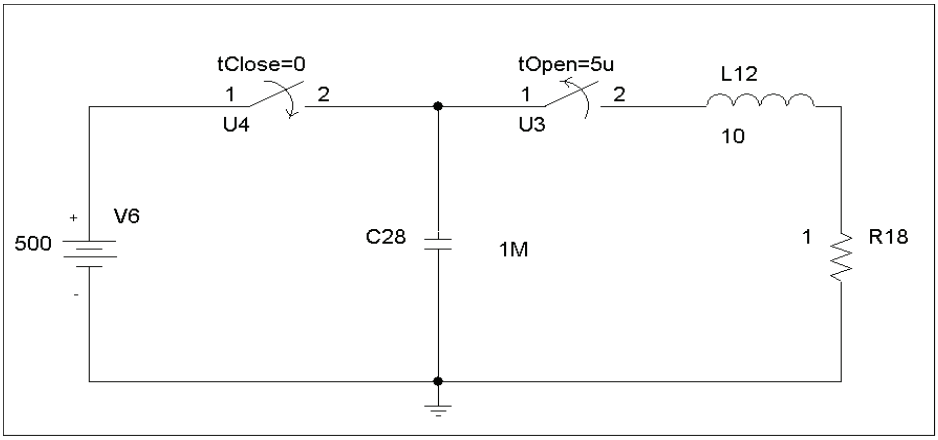


Fig. 4 – PD *signal generator*.

4 High Frequency Model

The lumped parameters for the HV winding are as shown in the **Table 1**. DC Resistance of the winding was done by knowing the design parameters and the resistivity of the conductor used.

Table 1
High frequency model lumped parameters.

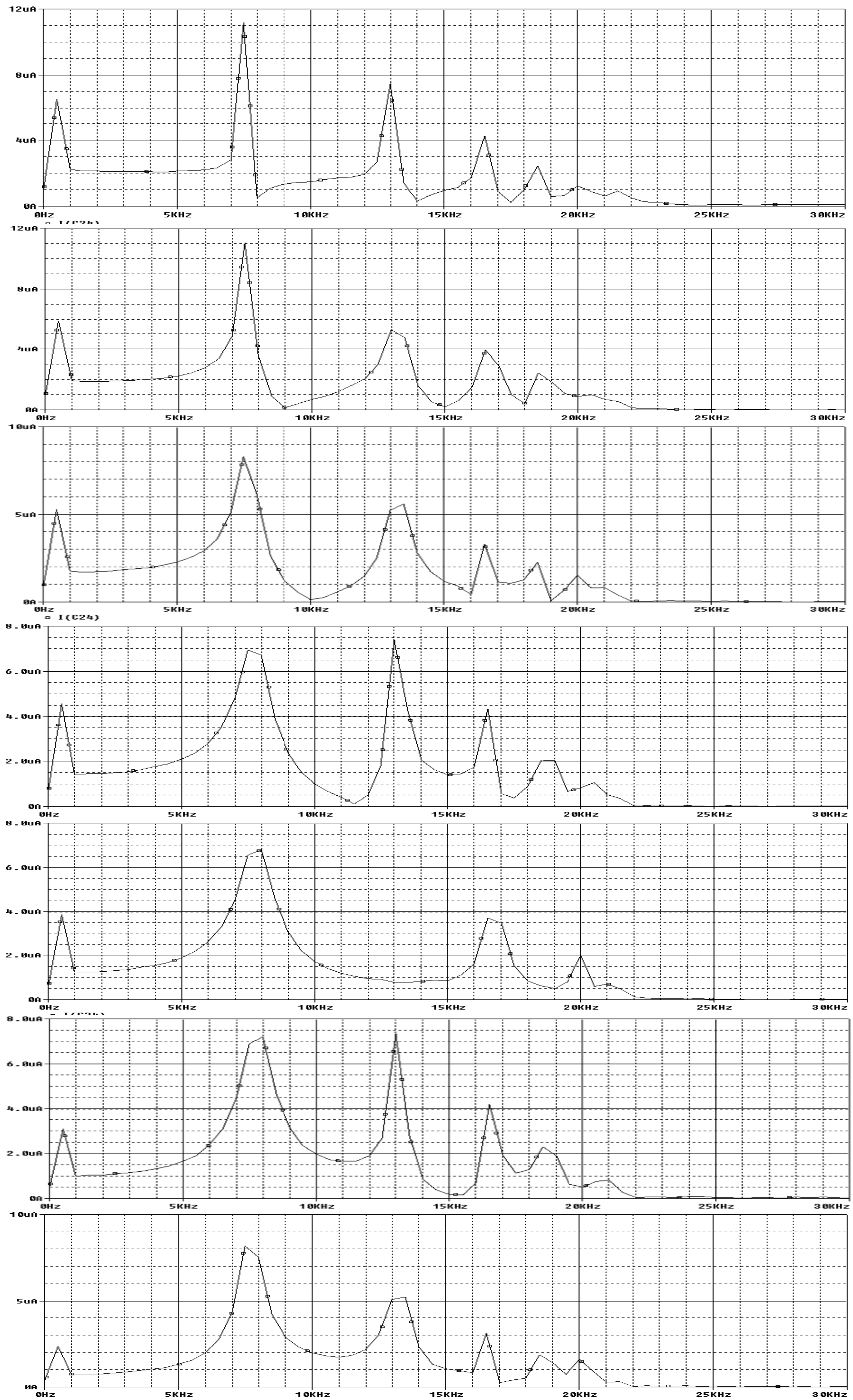
Parameter	Analytical results	Simulation results
C_g	1.946 × 10-11	1.99 × 10-11
C_s	3.11966 × 10-11	3.0108 × 10-11
L	2.075 H	1.47 H
R	1.6366 × 10-4 Ω	1.6366 × 10-4 Ω

Mutual inductances have been considered in the simulation using the coupling coefficients.

5 Results and Discussions

In first simulation, analytically calculated lumped parameters are simulated in ORCAD, and FFT of the captured bushing current signals for various PD locations are taken. Their corresponding frequency for peaks and troughs is used for the PD location estimation. Fig. 4 illustrates the FFT of various signals captured at bushing tap.

Using the series resonant peaks the PD location is estimated for the various signals and their accuracy is also evaluated as shown in **Tables 2**, **3** and **4**.


12uA
8uA
4uA
0A
0Hz
5KHz
10KHz
15KHz
20KHz
25KHz
30KHz
10uA
5uA
I(C24)
8.0uA
6.0uA
4.0uA
2.0uA

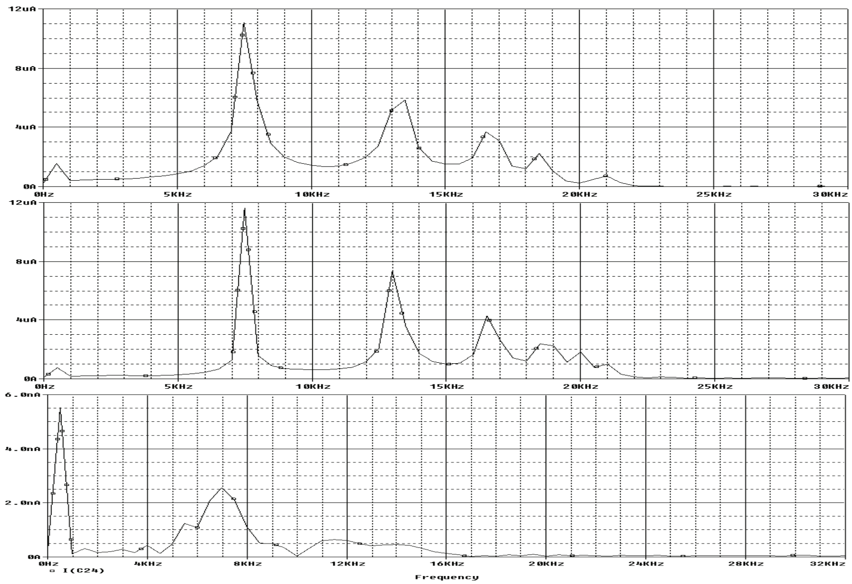


Fig. 4 – FFT *of the* PD *signal captured at bushing tap for various* PD *source locations for analytically calculated parameters*.

Table 2

Series resonant frequencies of the signals captured at bushing tap for input at all taps.

PD Location Algorithm				
PD Location	Series resonance frequencies			
	F1	F2	F3	F4
Line end	8	14	17.5	19
Tap 1	9	15	18	
Tap 2	10	16	19	
Tap 3	11.4	17.4	19.5	
Tap 4	13.5	19	20.5	
Tap 5	15.5	17.5	20	
Tap 6	16	17	19.5	
Tap 7	17.5			
Tap 8	18	19.5	20.5	
Tap 9				

Table 3

Lumped parameters derived from series resonance peaks.

Value of *LK* and *LC* from resonances f1 and f2 of Line end signal	
LC_s	3.50765E-09
LC_g	4.03863E-11

Table 4
Estimation of PD *location using series resonance peaks*.

Comparison between actual and measured PD Location						
Tap No	Actual PD position [%]	Estimated position due to F1 [%]	Actual Height	Measured height	Error in mm	Error in % height of winding
Bush	0	0	0	0	0	0
Tap 1	10	12.463	36	44.8668	8.8668	2.463
Tap 2	20	22.599	72	81.3564	9.3564	2.599
Tap 3	30	34.062	108	122.6232	14.6232	4.062
Tap 4	40	47.328	144	170.3808	26.3808	7.328
Tap 5	50	57.219	180	205.9884	25.9884	7.219
Tap 6	60	59.408	216	213.8688	-2.1312	-0.592
Tap 7	70	65.49	252	235.764	-16.236	-4.51
Tap 8	80	67.39	288	242.604	-45.396	-12.61
Tap 9	90	ND	324	ND	ND	ND

ND – Not Determinable

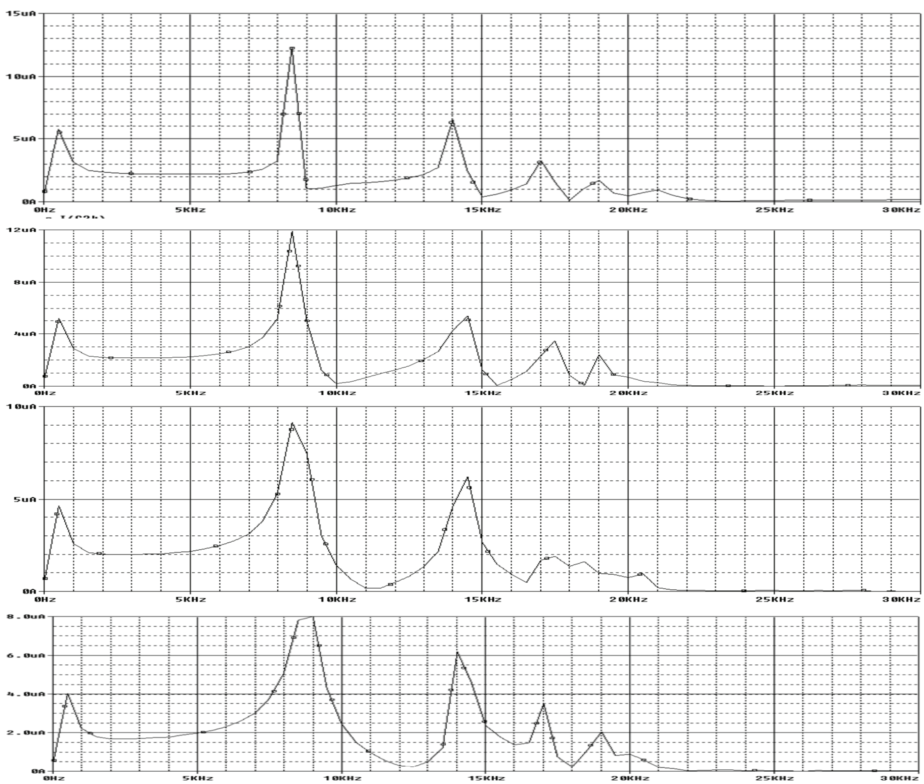


Fig. 5 – FFT *of the* PD *signal captured at bushing tap for various* PD *source locations for analytically simulated parameters*.

The corresponding PD location estimation for simulated design values as shown in **Tables 5**, **6** and **7**.

Table 5
Series resonance frequencies of the signals captured at bushing tap for input at all taps.

PD Location Algorithm				
PD Location	Series resonance frequencies			
	F1	F2	F3	F4
Line end	9.5	15	18	20
Tap 1	10	15.5	18.6	
Tap 2	11.5	16.6	18	
Tap 3	12.5	16	18	
Tap 4	14	18.5	19	
Tap 5	15.5	18.5		
Tap 6	16	18	19.5	
Tap 7	18.5	20		
Tap 8	19.6	19.5		
Tap 9	19.6			

Table 6
Lumped parameters derived from series resonance peaks.

Value of *LK* and *LC* from resonances f1 and f2 of Line end signal	
LC_s	2.21196E-09
LC_g	5.65494E-11

Table 7
Estimation of PD *location using series resonance peaks.*

Comparison between actual and measured PD Location						
Tap No.	Actual PD position [%]	Estimated position due to F1 [%]	Actual Height	Measured Height	Error [mm]	Error in % height of winding
Bush	0	0	0	0	0	0
Tap 1	10	6.304	36	22.6944	-13.3056	-3.696
Tap 2	20	22.393	72	80.6148	8.6148	2.393
Tap 3	30	31.369	108	112.9284	4.9284	1.369
Tap 4	40	43.051	144	154.9836	10.9836	3.051
Tap 5	50	53.297	180	191.8692	11.8692	3.297
Tap 6	60	56.506	216	203.4216	-12.5784	-3.494
Tap 7	70	72.087	252	259.5132	7.5132	2.087
Tap 8	80	79.534	288	286.3224	-1.6776	-0.466
Tap 9	90	79.534	324	286.3224	-37.6776	-10.47

6 Conclusion

The propagation of partial discharge pulses in the HV winding is analyzed based on the change in PD location. The high frequency model of the transformer was derived using both analytical calculation and simulations within an accuracy of ±5%. Calculation of PD location using the sectional transfer function from the design parameter gave PD location within accuracy of ±10% of the winding height. Maximum variation and error is noticed nearer to the neutral end as the resonant peaks are not prominent enough.

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