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Analysis of the Influence of Fault Resistance and SIR on the Distance Relay

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Abstract: This article proposes to verify the influence of fault resistance on the digital distance relay. To this end, a series impedance line (short line) of 230 kV was used for the simulations considering fault resistance values ranging from 5 ohms to 25 ohms. Furthermore, the SIR variation (0.2, 3, 12.75) was also taken into account in order to verify the impedance path for these boundary conditions. The experimental data and results show that the impedance behavior seen by the relay and the overreaching phenomenon caused by the increase in fault resistance.
Keywords: Faut resistance, SIR, variation, distance relay.

1. INTRODUCTION

The purpose of a protective relays is to clear the fault as quickly as possible, minimize the damage caused due to fault and restore the line quickly [1].Distance relaying, either phase or ground type, is frequently applied as the main protection of important transmission lines. Distance relays perform a comparison between the positive-sequence apparent impedance measured from one terminal of the line and the relay operation characteristic to decide between line tripping or not. This procedure is carried out after the fault detection, and is based on the line impedance for the trip decision [2].

The most common technique used is based on the evaluation of signal amplitudes of currents and voltages at the fundamental frequency [3]–[6]. This approach is referred to as impedance based measurement technique.

During a low resistance fault, it is possible to achieve reasonable accuracy using this method, since the effective impedance between the relay and ground is close to the apparent impedance measured by the relay. Traditional distance relaying is designed to operate as primary protection (first zone, Zone 1) for a limited line impedance value. For faults outside this zone, distance relays can be used as backup protection, in time-delay coordinated stages (second and third zones) [7].

Fault resistance presents a challenge to establish proper distance protection settings for transmission lines [8]. A common utility practice to deal with this challenge is to use representative fault resistance values to establish the size of Zone 1 protection [9]. Existing methods for fault resistance estimation can be classified in two categories. The first group includes methods that use online information as part of the relay method [10]–[12], mainly for fault-location estimation. The second group includes methods that use offline information from one or both ends of the transmission line [13]–[17]. The main problem with these methods is that they require data synchronization [18].

Fault resistance is a critical variable in distance relaying. If not considered due to underreaching phenomenon, it may cause the misoperation of ground distance relays for internal faults. Still, because of the overreaching phenomenon, the unbalanced nature of loads and asymmetry of lines can affect the distance protection operation efficiency. Mainly due to these aspects, there is low precision in protection zone limits of ground distance relays [19].

Faults are common disturbances in power systems. This phenomenon is associated with different causes, such as insulators breakdown, lightning, equipment failure, and even trees or animals in contact with electrical equipment. Due to its stochastic nature, faults are also hardly avoidable, leaving to protection engineers the task of designing protection schemes that prevent severe system damages, eliminating the fault as fast, secure, and reliable as possible. In the history of electric power systems, protection engineers have developed such designs based on different approaches, such as reliability, security, selectivity, and coordination. These designs make use of different protection equipment, such as reclosers, circuit breakers, fuses, sectionalizers, and relays [2].

2. FAULT RESISTANCE EFFECT AND INFEED EFFECT DURING SINGLE-LINE-GROUND FAULTS

Fault resistance introduces an error in the distance estimation obtained with traditional distance relays, since in resistive faults, the distance between the relay and the fault point is not necessarily proportional to the impedance seen by the relay [2], [20].

Fig. 1 shows a phase-to-ground fault with fault resistance in a two-terminal system [18].

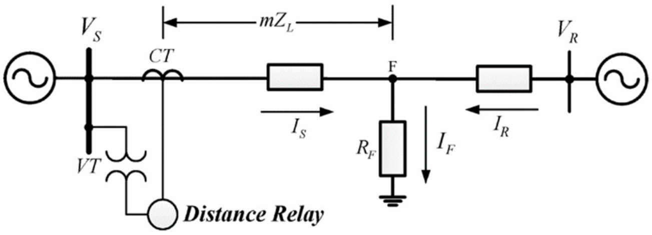


Figure. 1. Phase-to-ground fault with the infeed effect [18].

The errorintroducedbythefaultresistance for a symmetricalfault [1] isgivenby (1):

$$Z = \frac{V_S}{I_S} = Z_F + R_F I_F = mZ_L + R_F\left(\frac{I_R}{I_S} + 1\right) \tag{1}$$

Where $I_S$is the fault current measured in the relay and I_F is the total fault current through fault resistance R_F.

The factor $I_R/I_S$is a complex number, which depends on source impedances behind the transmission-line terminals.

Equation (1) produces an overestimate of the distance to the fault because the relay does not measure the current contribution to the fault from the remote-end source (infeed effect) [8].

This current is generally associated with the presence of substations or generators in adjacent buses and may cause the incorrect relay operation. This problem results from a reactance error in the apparent impedance measurement, which can cause sub-reaching or over-reaching errors in distance relays, especially for resistive faults close to the first zone boundary [21].In addition, there are two unknowns in the equation (1): the fault location and fault resistance. Consequently, the calculation of fault resistance is not possible using data from only one end of the line. Using a two-terminal approach, the voltage at the fault point *m* is [18]:

$$V_F = V_S - mZ_L I_S \tag{2}$$

$$V_F = V_R - (1-m) Z_L I_R \tag{3}$$

Since these equations are simultaneously valid during a single ongoing fault, we have [18]:

$$m = \frac{(V_S - V_R) + Z_L I_R}{Z_L (I_S + I_R)} \tag{4}$$

The fault resistance can be achieved by (1) and (4), which is [18]:

$$R_F = \frac{V_S - (V_S - V_R + Z_L I_R) \cdot \left(\frac{I_S}{I_S + I_R}\right)}{I_S + I_R} \tag{5}$$

The fault resistance causes an underreaching phenomenon in distance relaying, as shown in Fig. 2 [19].

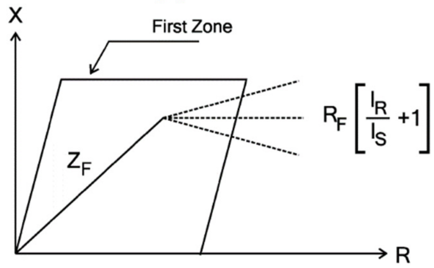


Figure 2. Underreaching in distance relaying due to fault resistance [19].

A way to overcome this problem is to compensate the fault resistance. Traditional distance relays achieve this compensation using a quadrilateral characteristic that depends on the angle between I_R and I_S [20]. By applying this technique, it is possible to obtain a better fault resistance coverage and arc compensation, without problems associated with overload misoperation of the distance relay.Other shapes of distance relay trip zones are also possible [20], [22]–[24]. However, the fault resistance compensation is limited by the maximum line loading, which may cause relay misoperation for faults with high-fault resistance value [19].

To overcome this limitation, recent works suggest the usage of fault resistance estimation in distance relaying [25]–[29]. Those works provide a fault resistance estimate and compensation prior to the trip decision in order to accomplish better results in digital distance ground relaying. The fault resistance is estimated by using symmetrical components or modal analysis, restricting the usage of these techniques in balanced systems and equally transposed transmission lines [19].

All phasor quantities in (5) are available from digital fault recorders at both ends of the transmission line, and Z_L is the positive-sequence impedance of the line. The voltages V_S, V_R and currents I_S, I_R in the equation depend on the fault type in Table 1 [8], where k_0 is the compensation factor for the zero-sequence current and I_R is the residual current. However, the calculation of using (5) requires time synchronization of R_F the data from the digital fault recorders at both ends of the line.

Table 1. Voltage and current for fault resistance estimation in different fault types.

Fault type		Voltage	Current
Phase	A-B	$\overrightarrow{V_A} - \overrightarrow{V_B}$	$\overrightarrow{I_A} - \overrightarrow{I_B}$
	B-C	$\overrightarrow{V_B} - \overrightarrow{V_C}$	$\overrightarrow{I_B} - \overrightarrow{I_C}$
	C-A	$\overrightarrow{V_C} - \overrightarrow{V_A}$	$\overrightarrow{I_C} - \overrightarrow{I_A}$
Ground	AT	$\overrightarrow{V_A}$	$\overrightarrow{I_A} + k_0\overrightarrow{I_{a0}}$
	BT	$\overrightarrow{V_B}$	$\overrightarrow{I_B} + k_0\overrightarrow{I_{a0}}$
	CT	$\overrightarrow{V_C}$	$\overrightarrow{I_C} + k_0\overrightarrow{I_{a0}}$

Fig. 3 shows the connections of the zero, positive and negative sequence diagrams for a single-phase phase-to-ground short circuit.

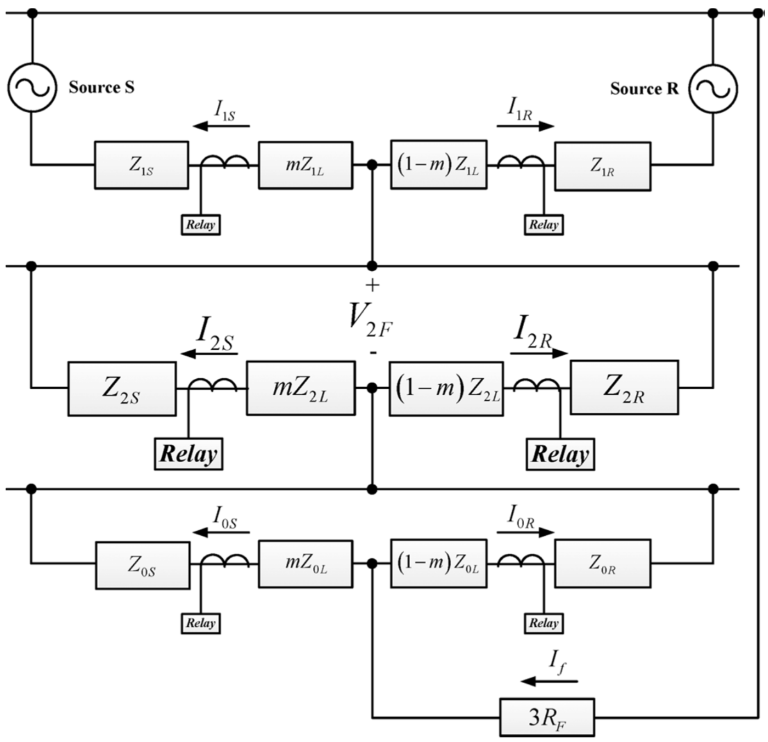


Figure 3. Sequence networks for a single-line-to-ground fault at fault location *m* [8].

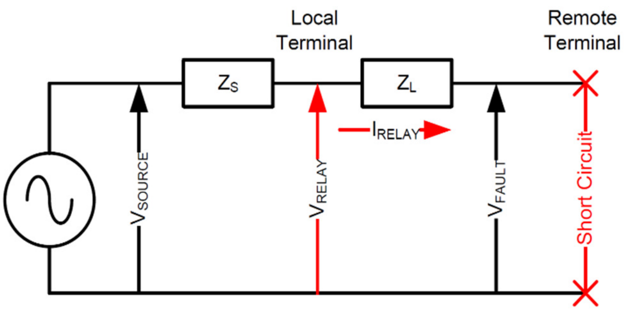
3. SOURCE IMPEDANCE LOAD (SIR)

The length of the line is often used to help determine the protection scheme that is specified. It is also used to guide the relay setting engineer in determining what elements can be applied and/or selecting margins. The length of a line can be defined by physical distance, impedance, or its source impedance ratio (SIR). The SIR is the ratio of the source impedance, Z_S, to the line impedance, Z_L [30].

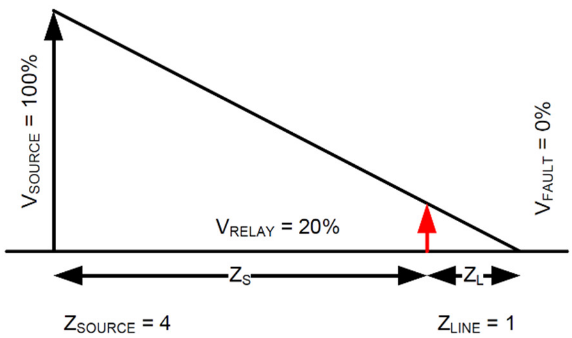
The SIR is well established in the industry as the preferred method for classifying the electrical length of a line for the purpose of applying protective relays. IEEE C37.113, IEEE Guide for Protective Relay Applications to Transmission Lines [31] classifies line length based on SIR as follows:

- Long line (SIR < 0.5)
- Medium line (0.5 < SIR < 4)
- Short line (SIR > 4)

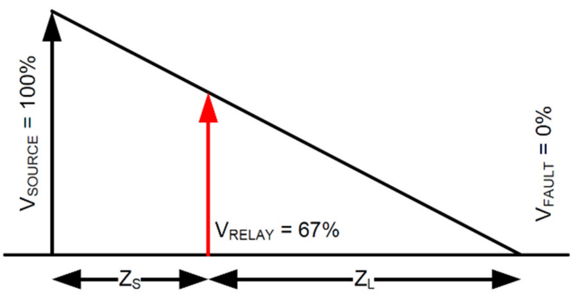
SIR is useful in classifying line length because the SIR is a convenient way to characterize a voltage divider network [30]. Fig. 4 illustrates the circuit for analysis.



(a) Voltage Divider Circuit.



(b) SIR = 4, Short Line.



(c) SIR = 0.5, Long Line.

Figure 4. SIR as Voltage Divider Circuit [30].

It can be seen that for an SIR > 4, the voltage at the relay will be less than 20 percent nominal. This voltage divider nature of SIRs is useful in justifying the application of pilot protection. The voltage dip at the local bus for an end-zone fault is large for a high SIR line terminal. We can see from Fig. 4b that time-delayed clearing for an end-zone fault on the SIR = 4 line would cause the voltage to dip to 20 percent of nominal [30].

Waiting for Zone 2 time-delayed clearing would impress this low voltage on adjacent loads for a significant time, which may result in initiating load transfer schemes, starting standby generation, motor stalling, and dropout of sensitive electronic loads [32].

The recommended method for calculating the SIR is to place a fault at the remote line zone boundary (the remote bus) and calculate the source impedance as the voltage drop from the so-called infinite bus to the relay divided by the current through the relay [30].

4. ANALYSIS OF THE IMPEDANCE BEHAVIOR CONSIDERING FAULT RESISTANCE AND SIR

The implementation was carried out in the ATPDraw software considering a single-phase fault on bus S, where the voltage (V_S) and current (I_S) signals for the applied short circuit were collected, as illustrated in Fig. 1.

After reading the control data (electrical system information) and the defect data, the program begins the pre-processing phase of the data related to the defect by executing a linear interpolation on the original data read, lowering the initial sampling rate of these "original data", obtaining the so-called "intermediate data", with a lower sampling frequency (in the case of simulated data). Next, the algorithm performs low-pass filtering, using a Butterworth filter and finishing the pre-processing stage of the input data.

In the signal post-processing stage, detection work is carried out (combination of fault units), with or without the emission of the trip signal. Distance protection works based on dividing the fundamental frequency components of the voltage and current signals at the relay point (Z = V/I).

The calculated apparent impedance is compared with the range point impedance. The algorithm indicates which type of fault occurred in the electrical system, that is, it presents the type of fault (AT, BT, CT, AB, BC, CA, ABT, BCT, CAT, ABC or ABCT, depending on the distance units that operated).

Fig. 5 shows the impedance behavior considering the variation of fault resistance starting at 5 Ω up to 20 Ω. Furthermore, the simulation considered the SIR equal to 0.2, that is, a strong source.

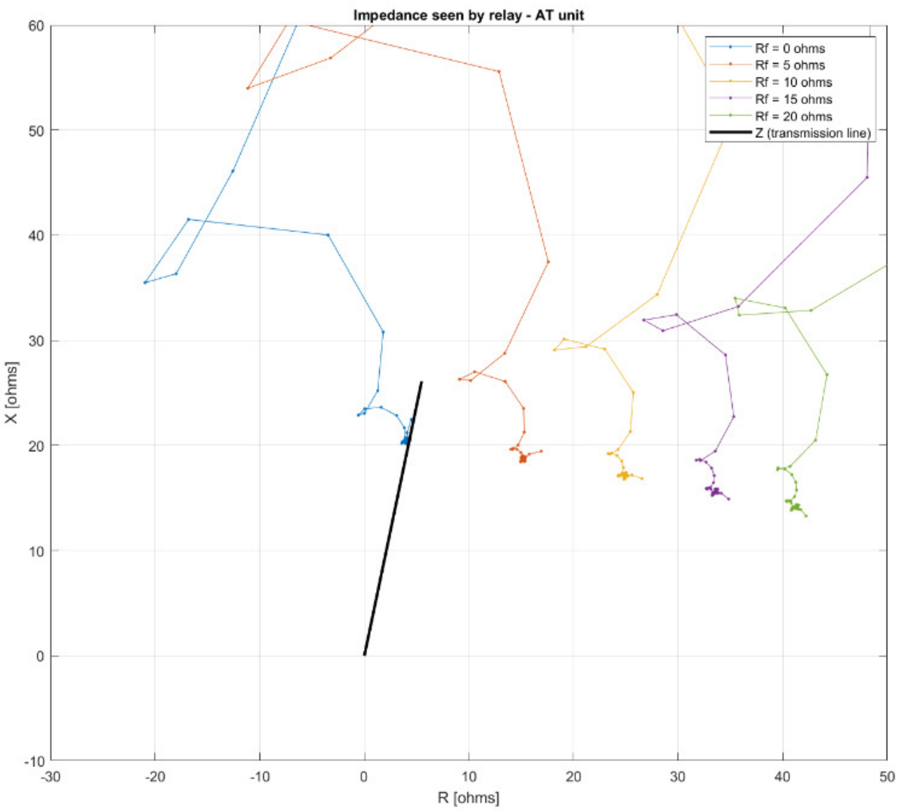


Figure 5. Impedance seen by the relay: R_F = 5Ω to 20 Ω, SIR = 0.2.

It is observed that with the increase in fault resistance the impedance moves away from the transmission line, and consequently, it becomes difficult for distance protection. In this case, relays with quadrilateral characteristics are recommended to increase coverage of the protection zone.

Figure 6 shows the impedance behavior considering the variation in the fault resistance in Fig. 5, however, the SIR value is equal to 3.

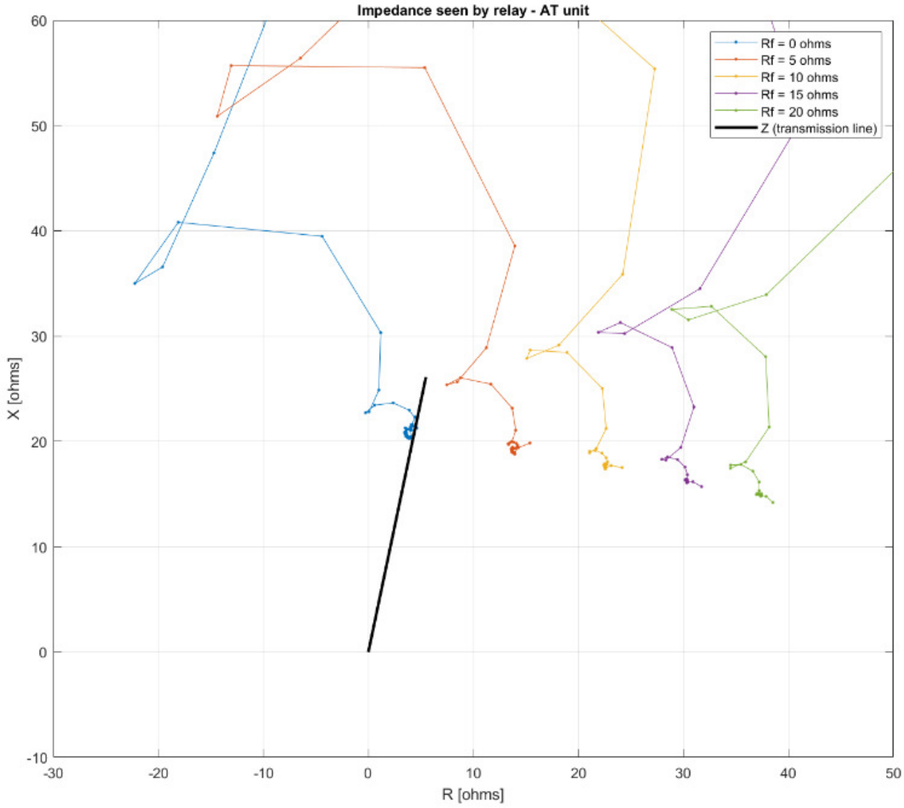


Figure 6. Impedance seen by the relay: R_F = 5Ω to 20 Ω, SIR = 3.

Figure 7 maintains the fault resistance variation and changes the SIR value to 12.75.

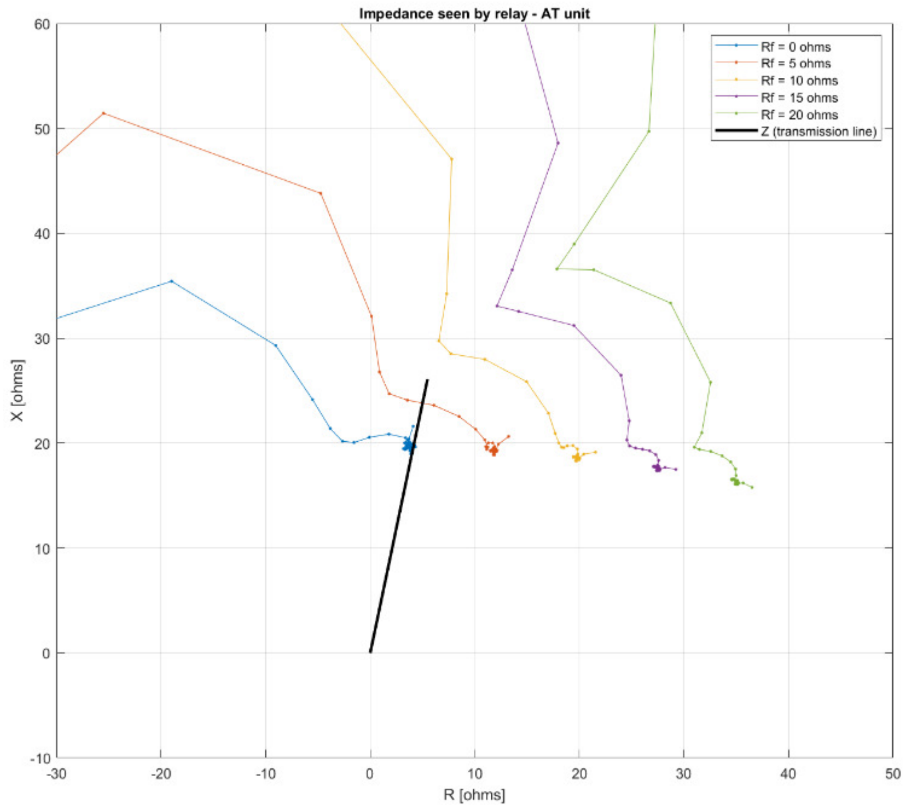


Figure 7. Impedance seen by the relay: R_F = 5Ω to 20 Ω, SIR = 12.75.

For the relay's operating condition, the following condition was considered: if the value of Z (impedance seen by the relay) is lower than the impedance of the range point, it was assumed that there is a fault in the line between the relay and the range point. However, in the presence of fault resistance in the fault path, it was observed that Z was not proportional to the reach impedance. For this reason, a fixed characteristic, conventional Mho relay scheme (for example) may force the relay to overreach/underreach due to its limited resistive coverage, most likely in Zone 1 and Zone 2. In this case, the application of a polarized is also indicated.

5. CONCLUSION

Throughout the study, the variation of fault resistance and SIR were evaluated for a single-phase phase-to-ground short circuit in a short-length transmission line (51 km). A realistic 230 kV high voltage network model is used for the necessary investigations. The network model was implemented using the EMTP-ATP program.

Based on the simulation results, it is found that the fault resistance has a significant effect on the characteristics of the ground fault. Simulations were presented considering the variation of fault resistance and SIR, where it was observed that if the underreach phenomenon is not considered, it could cause malfunction of the ground distance relays for internal faults.

Additionally, it was noted that identifying when a line is electrically shorted is important for determining the appropriate line protection scheme to apply and for determining adequate margins for underreach and unconditional trip protection elements.

With this, knowing the SIR is especially important for short lines, as the SIR is a useful way of quantifying a voltage divider network that will show the relay voltage for a fault at the edge of the protection zone.

Finally, it can be noted that if there is very little difference between the voltage at the relay for an in-zone fault and an out-of-zone fault, measurement errors from the instrument transformer and the relay will become significant and the relay will have difficulty differentiating between an internal and external fault.

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