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Optimum Placement of Measurement Devices on Distribution Networks using Integer Linear K-Means Clustering Method

***Abstract**: In distribution networks, PMU (Phasor Measurement Unit) is required for each node or bus, but the cost of installing PMU is quite expensive, so optimization of PMU placement is required. This study uses the Integer Linear K-means Clustering method and uses the parameters of voltage, current and impedance. This method is a combination of Linear Integration and K-Means methods used for optimizing PMU placement. The object used for research is the Bendul-Merisi distribution network which has 11 buses. The results showed that the Integer Linear K-means Clustering method can be used for PMU placement optimization. With a network of 11 buses, only 3 PMU is needed, resulting in a reduction in the number of PMU by 73%.*

Streszczenie.** W artykule zaproponowano metodę optymalizacji rozmieszczenia w sieci układów do pomiaru fazy. Zastosowano kombinację metod: Linear Integration I K-means. Na przykładzie sieci w Bendul Merisi (Indonezja) zredukowano liczbę mierników o 73%. **Optymalizacja rozmieszczenia urządzeń do pomiaru fazy PMU na przykładzie sieci rozdzielczej w Indonezji

Keywords: Integer Linier K-Means, Cluster, Phasor Measurement Unit, Optimal.
Słowa kluczowe: urządzenia do pomiaru fazy PMU, sieć rozdzielcza .

Introduction

Operation of the electricity network system requires planning, operating, and monitoring accurate data. Monitoring and measurement is carried out by the State Electricity Company (PLN) continuously. Measurements are made using a measuring instrument called the Phasor Measurement Unit (PMU) [1-4]. But PMU measuring devices are very expensive. New innovations are needed to reduce the number of installed PMUs with optimal placement so that they are still able to observe all buses. Some researchers have done with several methods including the method, Integer Linear Programming (ILP) to reduce the number of PMU. This study applies the concept of zero injection and the results are several meters of measurement on buses that can be represented by other buses [5]. Researchers [6-7] have examined using the Weight Least Square (WLS) method based on voltage and current parameters for placing PMUs with the State Estimator Distribution System over a large area and showing good results. Next is the technique of using power for PMU placement and monitoring and the results can reduce the amount of PMU usage [8]. Binary Imperialistic Competition (BICA) algorithm from the same research uses the concept of zero injection bus, this concept uses conventional rules and new rules to reduce the number of PMUs and the results have more covariance [9]. Other studies using the Approximately Optimal Position PMU (AOPP) method are used for PMU placement by identifying search space using deterministic concepts, and the results are found in certain spaces [10]. Researchers [11] used the Binary Particle Swarm Optimization (BPSO) algorithm with integer data and PMU placement in the appropriate location. Furthermore, the Kohonen method was examined by researchers [12] with the concept of clusters and the results occurred resulting in the formation of new clusters. Future studies use the K-means algorithm. In his research the basic algorithm is K-means and K Means grouping results, the basic algorithm K-Means has been implemented in the same dataset and the results are very complex for large data distances [13-24]. Research [25] uses the concept of Binary Integer Programming (BIP) using binary vectors 1 and 0. This algorithm will update the minimum and maximum limits, but make the results less than optimal. Linear Integer with the concept of One Depth Unobservability is examined by [26] and the result is only one bus that is not supervised and the results are less than optimal. Placement of PMU with Integer Linear Programming based on network topology is also examined [27] and the results can be determined by considering the connected bus, the results are limited to integer values 0 and 1..

This paper presents a new concept that combines the Linear Integer method and the K-Means method for clustering and optimizing PMU placement in the Bendul-Merisi Surabaya Indonesia distribution network. This combination has the advantage of being able to calculate non-integer random data with more accurate results. So we get the results of reducing the number and determination of the optimal PMU location.

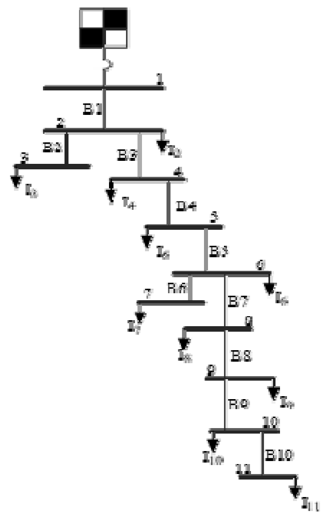

Fig 1. Bendul-Merisi Single-Line Distribution Network Surabaya Indonesia

Formulation of Measurement Unit In Distribution Network

The distribution network in Figure 1 is an open-loop radial distribution network. In open-loop distribution networks, it is easy to cluster. Clusterization based on bus voltage can use the Linear Integer method [9]. In this method, the data used are only values 0 and 1 for optimizing the placement of the PMU on the network. Meanwhile, the data taken from the Bendul-Merisi distribution network are voltage, current, and impedance data whose values are not integers. With this data, the K-Means method is used for clustering and optimizing PMU placement.

Combining the integer liner method with the K-Means method for clustering and optimizing PMU placement is the core of this research. The linear integer method is used to get the value of the voltage drop on each bus. The value of the voltage drop obtained plus the data from the measurement of current and impedance is used for the clusterization process and optimizing the placement of the PMU on the distribution network.

In the distribution of Bendul-Merisi single line consisting of 11 buses and installed 11 PMU. Next, make a cluster. then arranged in the equation. Each data set is constructed by a binary dimension, which indicates a meter on the bus with symbol 1 if not 0 is shown in equation (1).

(1) $$A_{kxm} = \begin{cases} 1 \textit{ if } k = m \\ 1 \textit{ if k and m connected} \\ 0 \textit{ if not connected} \end{cases}$$

$$A_{kxm} = \sum_{j=1}^{m} X_j \geq M$$

subject to $m \in \{0,1\}, j \in \{0,1\}$

where, A_{kxm} : Matrix relationship between buses,

X_j: Measuring meter, M : Number of buses.

From Figure 1 by applying Kirchoff's Law, the injection current I can be formulated against channel B then the following equation (2) is obtained.

(2)

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6 + I_7 + I_8 + I_9 + I_{10} + I_{11}$$
$$B_2 = I_3$$
$$B_3 = I_4 + I_5 + I_6 + I_7 + I_8 + I_9 + I_{10} + I_{11}$$
$$B_4 = I_4 + I_5 + I_6 + I_7 + I_8 + I_9 + I_{10} + I_{11}$$
$$B_5 = I_5 + I_6 + I_7 + I_8 + I_9 + I_{10} + I_{11}$$
$$B_6 = I_7$$
$$B_7 = I_8 + I_9 + I_{10} + I_{11}$$
$$B_8 = I_9 + I_{10} + I_{11}$$
$$B_9 = I_{10} + I_{11}$$
$$B_{10} = I_{11}$$

Furthermore, from equation 2 it is formulated in the form of a BIBC matrix (Bus Injection to Branch Current) in the form of a Bendul-Merisi matrix containing 11 PMU of inter-bus connections (11x11) as in equation (3).

(3)

$$[BIBC] = \begin{bmatrix} 1&1&1&1&1&1&1&1&1&1 \\ 0&1&0&0&0&0&0&0&0&0 \\ 0&0&1&1&1&1&1&1&1&1 \\ 0&0&0&1&1&1&1&1&1&1 \\ 0&0&0&0&1&1&1&1&1&1 \\ 0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&1&1&1&1 \\ 0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1 \\ 0&0&0&0&0&0&0&0&0&1 \end{bmatrix}$$

The '1' numbers in the BIBC matrix expresses the relationship between the current and the channel in the distribution system of the slurry of the smelter, otherwise, the number 0 indicates no relationship between the current and the channel in the distribution system. Then we find the equation (4) and (5).

(4) $$[B] = [BIBC]x[I]$$

(5)

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \\ B_7 \\ B_8 \\ B_9 \\ B_{10} \end{bmatrix} = \begin{bmatrix} 1&1&1&1&1&1&1&1&1&1 \\ 0&1&0&0&0&0&0&0&0&0 \\ 0&0&1&1&1&1&1&1&1&1 \\ 0&0&0&1&1&1&1&1&1&1 \\ 0&0&0&0&1&1&1&1&1&1 \\ 0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&1&1&1&1 \\ 0&0&0&0&0&0&0&1&1&1 \\ 0&0&0&0&0&0&0&0&1&1 \\ 0&0&0&0&0&0&0&0&0&1 \end{bmatrix} x \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \\ I_8 \\ I_9 \\ I_{10} \\ I_{11} \end{bmatrix}$$

Topological networks are radial in tissu Bendul Merisi is used to determine the optimal position of the PMU by calculating the voltage drop on each bus. That is, the value of the voltage due by the matrix in equation (6).

(6)

$$\begin{bmatrix} V_1 - V_2 \\ V_1 - V_3 \\ V_1 - V_4 \\ V_1 - V_5 \\ V_1 - V_6 \\ V_1 - V_7 \\ V_1 - V_8 \\ V_1 - V_9 \\ V_1 - V_{10} \\ V_1 - V_{11} \end{bmatrix} = \begin{bmatrix} Z_{12}&0&0&0&0&0&0&0&0&0 \\ Z_{12}&Z_{23}&0&0&0&0&0&0&0&0 \\ Z_{12}&0&Z_{24}&0&0&0&0&0&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&0&0&0&0&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&0&0&0&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&Z_{67}&0&0&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&0&Z_{68}&0&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&0&Z_{68}&Z_{89}&0&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&0&Z_{68}&Z_{89}&Z_{910}&0 \\ Z_{12}&0&Z_{24}&Z_{45}&Z_{56}&0&Z_{68}&Z_{89}&Z_{910}&Z_{1011} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \\ B_7 \\ B_8 \\ B_9 \\ B_{10} \end{bmatrix}$$

$[\Delta V]$is the change in voltage that can be found using formulas such as equation 7

(7)

$$[\Delta V] = [BCBV]x[B]$$

Equations 2 - 7, it is used to calculate the drop voltage at the branch, bus voltage or branch current. All these data sets are needed for clustering process, to minimizing the number of PMU.

Clustering Method Of PMU Using Integer Linier K-Means Algorithm

Clustering is a method of grouping some data that has the same characteristics. According to research [14-24] is the process of combining data into several groups so that, data in one cluster has a maximum level of similarity.

There are various methods to measure the value of similarity between objects. The cluster technique used is the K-Means Linear Integer method. Voltage, current and impedance parameters. To calculate distances, it's called Euclidean distances. For example, 3 sets of data voltage (Vx), current (Ix), impedance (Zx) are shown in equation (8)

(8)

$$V_x \in \{V_1, V_2, ..., V_n\}$$
$$I_x \in \{I_1, I_2, ..., I_n\}$$
$$Z_x \in \{Z_1, Z_2, ..., Z_n\}$$

Data in equation (8) to be grouped into several clusters, then the member of each cluster is determined randomly. Every cluster will have average data, which is generated from members. This average is called centroid (Vcx, Icx, Zcx). Distance measurement by the Euclidean method can be written for each cluster with equation (9).

(9)

$$D_x = \sqrt{(V_x - V_{cx})^2 + (I_x - I_{cx})^2 + (Z_x - Z_{cx})^2}$$

From equation (9), every single data produces a single distance (Dx). The next step is to evaluate the minimum Dx that indicates a member of an appropriate cluster. When minimum Dxs are added together, it results in SSE (Sum Square Error). The formula is shown in equation (10).

(10)

$$SSE = \sum_{i=1}^{k} \sum_{p \in C_i} D(p, m_i)$$

where: $p \in C_i$ = each data point in cluster i, m_i = centroid from cluster i, D=distance nearest variance in each cluster i.

SSE values depend on the number of clusters and how the data are grouped into clusters. The smaller the SSE value the better the cluster results are made. The overall steps of this algorithm are illustrated in Figure. 2.

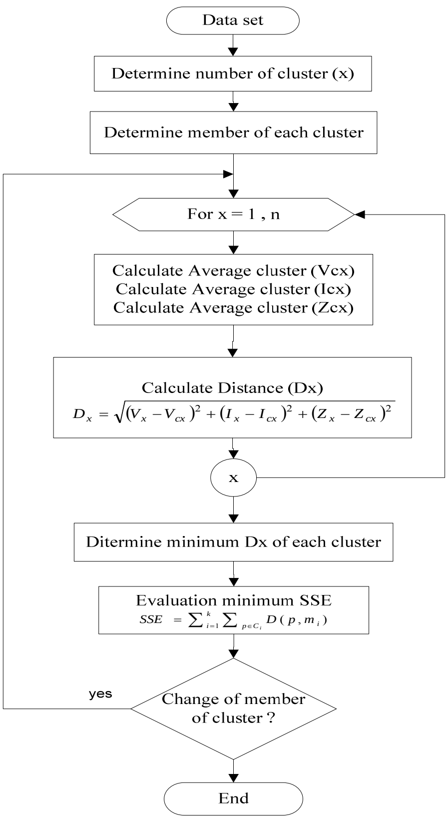

Fig 2. Integer Linear K-Means Algorithm

Results and Discussions

The Bendul-Merisi distribution network is used as a case study using the Integer Linear K_Means Clustering method. In this research, the network is divided into three clusters and two tests were conducted. The first test is carried out using only voltage and current parameters. The second test is done by adding the impedance parameters in order to determine the effect of the impedance in the placement of p.m.u. Table 1 shows the voltage and current data used in the first test. This data is data taken from the Bendul-Merisi single-line distribution network shown in Figure 1.

Table 1. The Bendul-Merisi distribution network data

Bus	Voltage	Current
2	19913	22.2
3	19910	6.2
4	19862	15.6
5	19818	15.6
6	19781	10.9
7	19771	24
8	19768	10.3
9	19739	16.2
10	19727	16.2
11	19721	13.2

The test begins by randomizing the bus number in Table 1 so that it can become Table 2. In Table 2, cluster 1 members are determined to be buses 6, 5, and 8, cluster 2 members are buses 9, 7, 11, and 10, while members of cluster 3 are buses 2, 4, and 3.

The voltage and current data in Table 2 are visualized using a two-dimensional graph of X and Y. The X-axis represents the voltage value and the Y-axis represents the current value. The visualization results of Table 2 are shown in Figure 3. In Figure 3, the buses are seen as members of clusters 1, 2 and 3.

Table 2. Random Bus with two parameters

Bus	Voltage	Current	Cluster
6	19781	10.9	1
5	19818	15.6	1
8	19768	10.3	1
9	19739	16.2	2
7	19771	24	2
11	19721	13.2	2
10	19727	16.2	2
2	19913	22.2	3
4	19862	15.6	3
3	19910	6.2	3

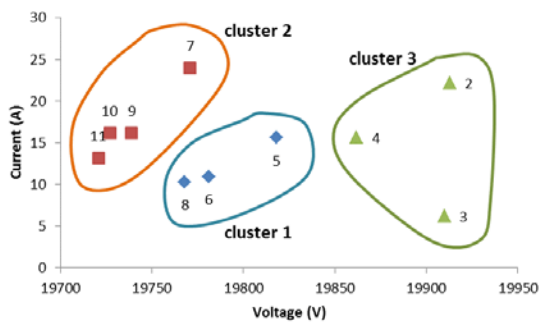

Fig 3. The visualization results of Table 2

The next step is to calculate the Euclidean distance from the center to each bus in each cluster. For example, cluster 1 has bus members with each voltage and current value and an average of Vcx and Icx which states the center of the position of all buses as shown in Table 3.

Table 3. Voltage and Current in cluster 1

Bus	Voltage	Current
6	V_6 = 19781	I_6 = 10.9
5	V_5 = 19818	I_5 = 15.6
8	V_8 = 19768	I_8 = 10.3
Average	V_{CX} = 19789	I_{CX} = 12.67

So that the distance of each bus to the center (D_x) can be calculated using the formula in equation (9), using only two parameters are voltage and current.

$$D_x = \sqrt{(V_x - V_{cx})^2 + (I_x - I_{cx})^2}$$

$$D_6 = \sqrt{(19781 - 19789)^2 + (10.9 - 12.667)^2} = 8.11590$$

$$D_5 = \sqrt{(19818 - 19789)^2 + (15.6 - 12.667)^2} = 29.19094$$

$$D_8 = \sqrt{(19768 - 19789)^2 + (10.3 - 12.667)^2} = 21.09189$$

In the first iteration, D_x values for all buses in clusters 1, 2, and 3 are calculated, the results are shown in Table 4. Focus on the Min column in table 4, it appears that for bus 7, the smallest D_x value is found in cluster 1. In this case, there is a change, bus 7 in cluster 2 changes into cluster 1. Visualization Table 2 with changes in cluster members is shown in figure 4.

Table 4. The First Iteration Data

Bus	Distance, Dx				Selected Cluster
	Cluster-1	Cluster-2	Cluster-3	Min.	
6	8.12	42.01	114.062	8.12	1
5	29.19	78.52	77.01	29.19	1
8	21.09	29.37	127.075	21.09	1
9	50,15	1.30	156,008	1.30	2
7	21.49	32.18	124.351	21.49	1
11	68.01	18.97	174.006	18.97	2
10	62.13	12.56	168.007	12.56	2
2	124.40	173.566	19.51	19.51	3
4	73.08	122.513	33.01	33.01	3
3	121.15	170.867	17.23	17.23	3
SSE				182.46	

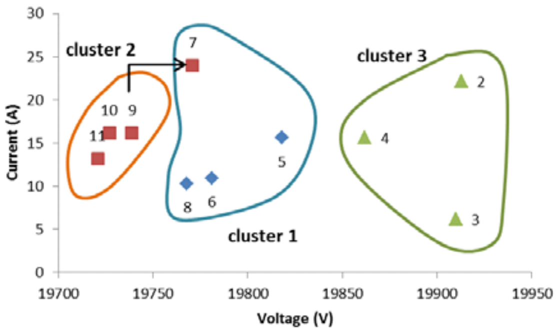

Fig 4. The visualization Table 2 with changes in cluster members

Table 5. The Final Iteration Data

Bus	Distance, Dx				Selected Cluster
	Cluster-1	Cluster-2	Cluster-3	Min.	
6	5.54	52.18	114.06	5.54	1
5	33.50	89.00	77.01	33.50	1
8	17.21	39.31	127.08	17.21	1
7	16.12	42.91	124.35	16.12	1
9	45.51	10.05	156.01	10.05	2
11	63.53	8.25	174.01	8.25	2
10	57.51	2.24	168.01	2.24	2
2	128.69	184.13	19.51	19.51	3
4	77.50	133.00	33.01	33.01	3
3	125.82	181.22	17.22	17.23	3
SSE				162.7	

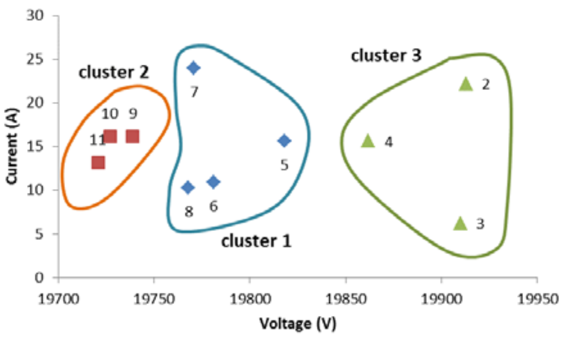

Fig 5. The final process of the cluster is convergen

Repeated steps are executed again until reaching a convergence condition where the value of SSE is constant. Final results are given in Table 5 and Figure. 5.

For optimal PMU placement, it is determined from the smallest Dx value of the buses in the same cluster. So that the smallest Dx value obtained in cluster 1 with buses 5, 6, 7, and 8 is on bus 6. Whereas in cluster 2 with buses 9, 10, and 11, the smallest Dx value is on bus 9. Similarly for cluster 3 with bus 2, 3, and 4, the smallest Dx value is on bus 3. So that the optimal PMU placement on buses 3, 6, and 9.

In the second test, three parameters are used, namely voltage, current, and impedance to determine the optimal placement of p.m.u in the Bendul-Merisi distribution network. Table 6 shows the random bus with three parameters and Table 7 shows the values of voltage, current, impedance, V_{CX}, I_{CX}, and Z_{CX} for cluster 1.

Table 6. Random Bus with three parameters

Bus	Voltage	Current	Impedance	cluster
6	19781	10.9	0.238	1
5	19818	15.6	0.098	1
8	19768	10.3	0.278	1
9	19739	16.2	0.049	2
7	19771	24	0.397	2
11	19721	13.2	0.270	2
10	19727	16.2	0.139	2
2	19913	22.2	0.079	3
4	19862	15.6	0.194	3
3	19910	6.2	0.056	3

Table 7. Voltage, Current, and Impedance in cluster 1

Bus	Voltage	Current	Impedance
6	V_6 = 19781	I_6 = 10.9	Z_6 = 0.238
5	V_5 = 19818	I_5 = 15.6	Z_5 = 0.098
8	V_8 = 19768	I_8 = 10.3	Z_8 = 0.278
Average	V_{CX} = 19789	I_{CX}= 12.67	Z_{CX} = 0.205

The distance of each bus to the center (D_x) can be calculated using the formula in equation (9), using three parameters are voltage, current, and impedance.

The results of the second test use three parameters, the last iteration data show the results that can be said to be the same compared to the first test using two parameters with a difference in value of 0.0001. This is due to the very small impedance value compared to the voltage and current values. So that the optimal placement of PMU, the same results are also obtained where the placement of PMU on bus 6 for cluster 1, bus 9 for cluster 2 and bus 3 for cluster 3.

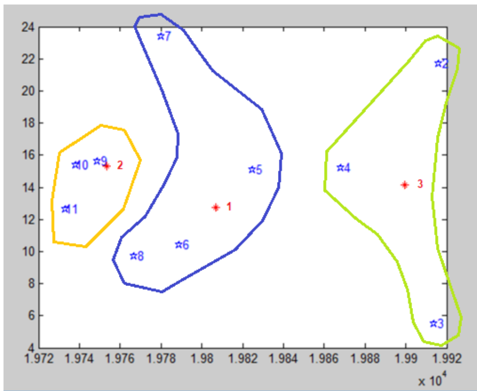

Fig 6. Visualize the results of determining the selected clusters for all buses using voltage, current and impedance parameters

To visualize the results of determining the selected clusters for all buses using an application program the results are shown in Figure 6. Figure 6 shows that buses 5, 6, and 8 enter cluster 1; buses 9,10, and 11 enter cluster 2;

buses 2, 3, and 4 enter cluster 3. These results are the same as the results of the first test using two voltage and current parameters.

In the research of PMU placement optimization using linear integer programming method [27], it showed quite good results. But there is a weakness if the input data for some parameters used is not an integer value, because the resulting value is an integer value so it is not accurate. Using the K-means method is more accurate, but if the data is too far from the center, the maximum and minimum limit values are needed. Therefore the combination of the two methods into the Integer Linear K-Means Clustering method becomes very accurate. Figure 4 shows this advantage where bus 7 which was originally in cluster 2 moves to cluster 1 by using the voltage, current, and impedance parameters.

Conclusion

Bendul-Merisi radial distribution network as the object of this study has 11 buses, so it is necessary to optimize the placement of PMU. The use of the Integer Linear K-Means Clustering method for PMU placement optimization shows good results. With a network of 11 buses, only 3 PMU is needed, resulting in a reduction in the number of PMU by 73%. Voltage, current, and impedance parameter data are data from measurements in the field and have fractional values. The results of the placement of PMU on buses 3, 6, and 9 are the results that are relevant to the Bendul-Merisi distribution network.

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Conflict of Interest

The author declares no conflicts of interest in this paper.

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