A Topology Identification Monitoring Terminal Based on the Pulse Current Characteristic Analysis

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Abstract: The low-voltage distribution network field wiring is very complicated and there are many changes in the relationship between households and changes, which brings great difficulties to the topology identification and line loss management of the transformer area. Aiming at the problems of low-voltage distribution areas physical topology recognition method based on distorted current signal and big data analysis in safety, recognition accuracy, and recognition efficiency, a method for recognizing the physical topology of the low-voltage distribution area based on pulse current characteristics fusion analysis was proposed. The Hilbert-Huang transform method was used to extract the characteristics of the current signal. The Space-time characteristic of charge method based on edge computing was used to realize the verification of low-voltage distribution area topology results. HPLC communication technology and measurement technology were combined to develop a low-voltage distribution area topology recognition monitoring terminal. The monitoring terminal was installed at the key nodes of the low-voltage distribution area such as low-voltage outlet cabinets, branch boxes and meter boxes. The monitoring terminal receives the topology recognition command of concentrator and main distribution area through the HPLC communication channel, uploads the topology recognition results, draws physical topology map of low-voltage distribution area in the main distribution area, and realizes the hierarchical measurement of low-voltage distribution area by the measurement function. The pilot operation of the on-site high-quality distribution area has proven that the monitoring terminal using the low-voltage distribution area physical topology recognition method based on the pulse current feature fusion analysis can map the low-voltage distribution area physical topology safely, quickly and accurately. Furthermore, it can provide strong support for the fine management of the low-voltage distribution area.

1. Introduction

The low-voltage distribution area constitutes an important part of the smart grid. As the end point of the grid transmission and the starting point for electricity consumption of the load equipment, it serves as a connecting link in the entire grid construction, which carries great significance to the overall construction of smart grid in China [1-2]. The low-voltage distribution area has a wide distribution area, non-uniform equipment standards, and high initial investment, resulting in long-term blank research on the intelligent monitoring system of the low-voltage distribution area, and its information monitoring and collection still rely on manual inspections, which is time-consuming, laborious and
costly. It is impossible to correctly plot the physical topological relationship of the low-voltage distribution area. As a result, there are no effective and reliable measures for line loss management. The equipment features coexistence of heavy overload and light no-load, so it is impossible to accurately locate the fault location [3-4]. At the same time, with the rapid increase in the number of low-voltage substations and power distribution stations, the existing efficiency of manual inspections is far from meeting actual needs. There is an urgent need for establishing a complete and reliable intelligent monitoring system to automatically identify the physical topology structure of the low-voltage distribution area, so that it is possible to accurately locate the fault link in the low-voltage distribution area, explore a new mode of active emergency repair, achieve full coverage of notification of power outages to all households and effectively reduce line loss [5]. Therefore, it is of great significance to study the intelligent monitoring terminal of low-voltage distribution area used for automatic recognition of physical topology.

At present, domestic and foreign research on power grid topology recognition of low-voltage distribution area is mainly divided into two categories: hardware topology recognition and software algorithm recognition. The hardware topology recognition is mainly to increase the recognition special equipment for the distribution area. For example, Gao Mengyou et al. [6] used a dedicated intelligent terminal, adopted a distributed feeder automation control method based on network topology recognition, and implemented "relay query" to realize automatic topology recognition and determine the interconnection switch position. Ying Jun et al. [7] built an overall framework for secondary verification through dedicated intelligent terminals, and developed a verification system with secondary verification functions, which improved the quality of topology recognition and verification. Li Ang et al. [8] used the μPMU special measuring device to compare the phase information based on the load flow calculation under different topological conditions with the measured phase information, and used the correlation analysis to distinguish the distribution network topology structure and topology changes. This method requires installation of topology recognition function equipment, and has low recognition success rate. On the other hand, domestic and foreign scholars have also proposed a variety of software recognition algorithms, which use the existing power grid information to recognize the topology. For example, using the voltage correlation analysis method based on dynamic time series segmentation, Zou Shirong et al. [9] judged the voltage correlation of different sequences in the sequence segment containing extreme points, and implemented topology check of the low-voltage distribution area. Lu Xin et al. [10] used the Pearson correlation coefficient method to identify the distribution area and analyze the mutual information between the electricity meters for the data collected synchronously at high frequency, which ensured data simultaneity and improved the accuracy of electrical topology judgment. Based on data association analysis, Yang Zhichun et al. [11] screened the characteristic voltage sequence in each type of distribution area, and used the Tanimoto similarity coefficient to calculate the correlation of the distribution devices in each group, thus achieving topology recognition of low-voltage distribution network.

Through investigation and analysis, it is found that, using technologies of cloud computing, artificial intelligence, big data, etc. so far, domestic experts and scholars have established state evaluation models, evaluated and verified the models for power equipment including transformers, relay protection, switch cabinets, overhead transmission lines [12]. The software algorithm-based recognition method can solve the problems of high cost and maintenance fee when replacing special hardware equipment, but there is huge data amount, and the requirements for accurate data recording are high.

Therefore, in response to the above problems, this paper combines the pulse current-based hardware identification method with the software-based pulse current time-frequency feature extraction method, and uses charge time-space feature method to check the topology recognition results. On this basis, an intelligent monitoring terminal combining pulse current communication technology, HPLC communication technology and measurement technology is developed, and accuracy and effectiveness of the recognition method are verified through simulation examples and field pilot tests.
2. System composition of low-voltage distribution area

The low-voltage distribution area is generally composed of transformer, cable, distribution area master meter, concentrator, branch box, molded case circuit breaker, meter box and user meter, and its system composition block diagram is shown in Figure 1. Due to the low informatization level of molded case circuit breaker, branch box and meter box, we lack effective monitoring methods. In view of this, monitoring terminals with physical topology recognition, metering and high-speed power line carrier communication functions are installed at key nodes of the low-voltage distribution area, such as branch box and meter box. Under the unified dispatch of the system master station platform and the concentrator, automatic drawing and hierarchical metering functions are possible for the physical topology of the low-voltage distribution area.

![Figure 1. System structure diagram of low-voltage distribution areas](image)

3. Research on key technologies for physical topology of low-voltage distribution area

3.1. Physical topology recognition method based on pulse current signal

According to the current signal transmission characteristics, the pulse current communication method is adopted to achieve physical topology recognition of the low-voltage distribution area, that is, all terminals in the low-voltage distribution area, including the monitoring terminal and the HPLC communication unit of the electric meter. Pulse current signals are generated in sequence according to the commands of the master station and the concentrator. The monitoring terminal or meter address is modulated into the pulse signal and sent to the power line of the low-voltage distribution area. Both the upper-level monitoring terminal and the concentrator in the same loop of the low-voltage distribution area can receive the pulse signal. Method based on Hilbert-Huang transform is used to extract the current signal features, and the monitoring terminal address in the pulse current signal is demodulated to access and record the time-frequency information and address information of the pulse current signal. The relevant information is transmitted to the concentrator for processing. After the concentrator reads it, physical topology of the lines in the low-voltage distribution area is plotted. In the specific design practice, a pulse current signal obeying certain frequency domain law is generated between the zero and fire wires of the electric power circuit through resistance switching method, and 800 Hz pulse current signal is generated between the zero and fire wires of the monitoring terminal and the HPLC communication unit of the electric meter through the MOSFET. The sent signal has a peak pulse current value of 420 mA, the circuit is safe and will not affect the power quality.
### 3.2. Pulse current signal feature extraction algorithm

The method based on Hilbert-Huang transform is used for feature extraction of current signal. By assuming that the signal \( V(t) \) is the quadrature component of the pulse current signal \( f(t) \), the Hilbert-Huang transform of the signal \( f(t) \) can be obtained.

\[
V(t) = f(t) \cdot \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{\infty} s(\tau) \frac{1}{\pi (t-\tau)} d\tau \tag{1}
\]

In formula (1), the Fourier transform of \( 1/\pi t \) is \( F\{1/\pi t\} = -j \cdot \text{sgn}(f) \), \( \text{sgn}(f) \) is a sign function, that is, it has the same sign as the independent variable, and modulus of the function value is 1. When \( f = 0 \), \( \text{sgn}(f) = 0 \).

The information carried by the current signal can be modulated on the amplitude, frequency and phase of the carrier signal \( f(t) \). Therefore, when performing signal feature identification, the amplitude, frequency and phase of the \( f(t) \) signal can be extracted, which is expressed as follows.

1) Estimation of the instantaneous amplitude of the envelope:

\[
\hat{A}(t) = \sqrt{v^2(t) + f^2(t)} \tag{2}
\]

2) Instantaneous phase estimation:

\[
\hat{\phi}(t) = \arctg \frac{v(t)}{f(t)} \tag{3}
\]

3) Instantaneous frequency estimation:

\[
f(t) = \frac{1}{2\pi} \frac{d}{dt} \left\{ \arctg \frac{v(t)}{f(t)} \right\} = \frac{1}{2\pi} \frac{d}{dt} \left\{ \phi(t) \right\} \tag{4}
\]

Based on the above feature extraction method, a feature matrix regarding the pulse current signal of the monitoring terminal is constructed. After Hilbert-Huang transform of the pulse current numbers collected by the four-layer topology concentrator, first-level branch, and second-level branch monitoring terminal, the estimated values of the instantaneous amplitude, instantaneous phase, and instantaneous frequency of the eigenvalue envelope are extracted to construct the characteristic matrix denoted as \( D = [A_{Ii}, \Phi_{Ii}, f_{Ii}] \). Where, \( A_{Ii} \) is the envelope amplitude matrix of the pulse current signal, \( \Phi_{Ii} \) is the instantaneous phase estimation matrix, and \( f_{Ii} \) is the instantaneous frequency matrix. According to the pulse current amplitude and frequency characteristics, the topology recognition pulse current signal is extracted from the numerous signals in the power supply circuit of the low-voltage distribution area, and the terminal address in the signal is analyzed after processing, as shown in Figure 2.

![Figure 2. Analysis diagram of pulse current](image-url)
result needs to be checked. In the existing application scenarios, the low-voltage branch box and the end user meter box are generally installed with monitoring terminals to achieve dynamic recognition of the low-voltage station area topology and the connection relationship between households and transformers. To compare the topological relationship diagram with the distribution automation master station system, the charge space-time feature method based on edge computing is used for topology recognition and verification. The specific steps are as follows.

1) The concentrator issues topology verification command through the carrier channel;
2) The meter box HPLC communication unit records the voltage zero-crossing time $t_i$ and uploads it to the concentrator through the meter box monitoring terminal;
3) The concentrator analyzes and records the time series of the zero-crossing points of each node $[t_1, t_2, ..., t_n]$. If the voltage zero-crossing time of the node time array is the same or within the set time deviation range, it can be determined as the in-phase node. The set time deviation is 10 μs. Therefore, the time series can be divided into three groups denoted as A, B, and C respectively;
4) The concentrator issues a state parameter collection command, and sets the collection time to $t_w$. The meter box monitoring terminal collects the current and power data of each branch as well as the corresponding time point information, and records the collected signals as $f_1(t)$, $f_2(t)$, ..., $f_n(t)$. The number of collected monitoring data is based on the number of network nodes. Where, $f_i(t) = [I_i, P_i]$, and the value range of $i$ is $[0, n]$. In this example, the value of $n$ is 43.
5) The collection time is set to accurately reflect the difference in user charge power. Under longer time, there are more obvious space-time charge differences, and the data amount is also bigger. Based on comprehensive consideration of the recognition accuracy and device hardware requirements, the collection time $t_w$ is set to 20 min.
6) According to Kirchhoff's current law, the sum of the current flowing into the node is equal to the sum of the current phasor flowing out of the node, and the node voltage remains unchanged. For a specific distribution area, the current will flow from the distribution area node to the lower-level branch nodes that flow along the physical line step by step until the user charge side. Set the node current and power of the distribution area concentrator to $(I_0, P_0)$, the outgoing node current and power to $(I_{A1}, P_{A1})$, $(I_{A2}, P_{A2})$, ..., $(I_{A6}, P_{A6})$, respectively. Then, $I_0 = I_{A1} + I_{A2} + I_{A3} + I_{A4} + I_{A5} + I_{A6}$; $P_0 = P_{A1} + P_{A2} + P_{A3} + P_{A4} + P_{A5} + P_{A6}$.

Take one of the second-level branch outgoing end nodes and the meter box-level incoming end nodes for illustration. If the topology identification result $Z_1$ matches the actual physical connection, the following charge relationship should be met.

\[
\begin{align*}
(I_{A62}, P_{A62}) &= (I_{A621} + I_{A622} + I_{A623} + I_{A624} + \Delta I_{A62}, \\
(P_{A621} + P_{A622} + P_{A623} + P_{A624} + \Delta P_{A62})
\end{align*}
\]  

(5)

Where, $\Delta I_{A62}$, $\Delta P_{A62}$ are the current and power line loss between the outgoing end node $A_{62}$ of the second-level branch and the incoming end node of the meter box. For the line loss of the same level, since the line is very short, it can be ignored. The cross-linking relationship between the outgoing end node of the level branch and the meter box level, household meter in the example is shown in Figure 3.

Figure 3. Structure diagram of low-voltage distribution areas
Calculate the current between the second-level branch outgoing end node and the meter box-level incoming end node in the topology identification result $Z_1$ according to the method in formula (5). If the relationship between the nodes meets the charge space requirements, the topology recognition result passes the comparison test. Otherwise, the recognition result fails, and the topology relation needs to be re-recognized through the topology recognition method based on the pulse current signal described in section 2.1. By analogy, the corresponding charge relationship model is established and verified for all nodes in the topology recognition result $Z_1$. If the requirements are met, the topology recognition result $Z_1$ is uploaded to the master station system.

4. Monitoring terminal design and implementation
The physical topology recognition method of the distribution area based on the pulse current signal is adopted to complete the collection of electricity consumption information of the node at the monitoring terminal, and edge computing technology is used for signal processing of the collected parameter data. The subordinate monitoring terminal and HPLC communication unit address are extracted through the time-frequency conversion method, which is then subject to fusion analysis with the topology recognition result of the monitoring terminal. The analysis and processing result is reported to the system master station.

In the hardware design, the above physical topology structure recognition method is implemented in the monitoring terminal. The monitoring terminal is composed of HPLC communication unit, metering unit, pulse current communication unit, central processing unit, RS-485 communication unit. The monitoring terminal completes data communication with the concentrator and electricity meter in the system through the HPLC communication unit. The metering unit completes the electricity consumption information metering at the installation node, receives pulse current signals from other monitoring terminals, and sends the monitoring terminal address to the upper-level node through the pulse current communication unit, then expands access to other equipment through RS-485 communication unit.

In the software design, the monitoring terminal, the concentrator and the electricity meter complete data communication through the 1376.2 and DLT645 interface communication protocols, respectively, transfer the data to the built-in database after the data collection, and then complete the data analysis and processing in the integrated algorithm module.

The structure of the monitoring terminal is shown in Figure 4.
4.1. HPLC communication unit
The HPLC communication unit adopts a modular design, and HZ3011 carrier chip is selected to construct an HPLC communication network to achieve data exchange with the concentrator, receive the concentrator meter reading and topology recognition commands. The principle block diagram is shown in Figure 5.

4.2. Measuring unit
The metering unit enables the functions of collecting electricity consumption data and receiving pulse current. The monitoring terminal has a built-in high-precision three-phase metering chip ATT7022E to form a metering unit. The metering chip is used in large-scale three-phase electric energy meter measurement. With the advantages of accurate measurement, stable performance and high cost performance, it uses low-cost coupling transformers to measure AC circuit voltage and shunt resistors to measure current. The divided voltage and the divided current are input to the chip, so that data such as power, power factor, and electric quantity can be calculated. The chip also has the functions of
measuring the working environment temperature, uploading the environment temperature data to the MCU, thus achieving measurement data calibration at different temperatures, reducing the temperature drift error, and then improving collection accuracy of the measurement circuit.

4.3. Pulse current communication unit
The pulse current communication unit is designed based on N-Channel QFET MOSFET, as shown in Figure 6.

![Figure 6. Schematic diagram of pulse current communication unit](image)

The central processor unit controls the MOSFET to generate a pulse current signal between the zero and fire wires of the electric power circuit, and modulates the monitoring terminal address into the pulse signal. The upper-level monitoring terminal and concentrator of the low-voltage distribution area can receive the pulse current signal, which use the method based on Hilbert-Huang transform to extract the current signal features, demodulate and record the monitoring terminal address in the pulse signal. After the concentrator finishes reading, the physical topology of the low-voltage distribution area is plotted.

4.4. Central Processing Unit
The master control MCU and storage circuit mainly implement the functions of data processing, carrier communication coordination and data storage. The MCU communicates with the memory and the measurement acquisition circuit through the SPI interface, while MCU communicates with the broadband carrier module through the UART interface. For work flow after power-on, the MCU initializes each interface, metering module and broadband carrier module, then controls the relevant load parameters collected by the metering module according to the program setting or the collection commands issued by the software platform, and inputs the status data to FLASH for storage. The central processing unit adopts GD32F405RGT6 chip, which uses Cortex-M4 ARM core, with a main frequency up to 168MHz. The chip has 144 pins in total, with small size, rich computing and interface resources, and its computing resources can meet the needs of distribution area topology recognition and verification algorithm based on Hilbert-Huang transform algorithm and space-time charge features. Its interface resources meet the needs of data exchange with the unit modules.

In the distribution area of the multi-level branch box and multi-meter meter box, a concentrator able to identify the physical topology of the low-voltage distribution area is installed on the low-voltage side of the transformer, and a monitoring terminal is installed in the branch box and meter box, as shown in Figure 7.
5. Application case analysis

5.1. Implementation ways of topology recognition
The physical topology recognition of the low-voltage distribution area is divided into branch recognition and meter box meter recognition. The branch recognition is performed by monitoring terminal and concentrator installed at key nodes such as the branch box and Π connection box. The meter recognition is performed by the HPLC communication unit of the meter and monitoring terminal of the box. The recognition steps are as follows.

1) The concentrator sends the file information of each meter in the distribution area to the meter box monitoring terminal through the power line carrier;
2) The concentrator sends time calibration command to each group of nodes to guarantee the time consistency between the household meter, meter box monitoring terminal and the concentrator;
3) The concentrator sends topology recognition commands through the power line carrier;
4) After the concentrator completes the recognition of the communication terminal address in the network, it obtains the number of nodes managed by the current communication network, which is recorded as n. Then, by the method of roll call, pulse current signals are generated from all the nodes capable of pulse current signal transmission in the current communication network.
5) After the roll call, the upper-level node of the pulse current signal transmission node uses Hilbert-Huang transform to extract the current signal features, and obtain the current signal characteristic frequency, envelope instantaneous amplitude, and instantaneous phase signal features. Whether such characteristic signal is the characteristic value of the pulse current signal is analyzed and determined according to the set value C. If it is true, the time stamp when the pulse current signal is received is recorded.
6) The branch communication terminals at all levels perform branch recognition respectively.
7) Generate the distribution area topology recognition result Z1.
8) Use the charge space-time feature method based on edge computing for topology recognition and verification.

5.2. Topology recognition based on monitoring terminal
After obtaining the addresses of the local HPLC communication unit and monitoring terminal, the concentrator obtains the number of nodes managed by the current communication network. Then, by roll call method, it makes all monitoring terminals and electricity meter HPLC communication units under the current communication network generate pulse current signals. After the HPLC
communication unit and the monitoring terminal receive the command signal from the concentrator, the pulse current communication unit generates a pulse current signal with a specified frequency, and modulates its address into the pulse signal. The frequency of the pulse current generated in the HPLC communication unit and the monitoring terminal is 800 Hz, and the current is 420 mA. Take the low-voltage distribution area system composition described in Figure 7 as an example, the physical topology recognition process is as follows.

1) The pulse current signal is generated in the electricity meter HPLC communication unit of the final meter box 1, which performs feature extraction on the current signal with the upper-level node monitoring terminal 1, monitoring terminal 1-1, and the meter box monitoring terminal 1-1-1 through Hilbert-Huang transform to obtain the feature frequency, envelope instantaneous amplitude, and instantaneous phase signal features of the current signal, receive and analyze the pulse current signal according to the set value, and record the communication address.

2) When the monitoring terminal 1-1-1 in the final meter box 1 sends a pulse current signal, the pulse current signal can be received at the concentrator, monitoring terminal 1 and monitoring terminal 1-1. The same feature extraction method as in 1) is used to extract the pulse current signal communication address. Therefore, it can be determined that the monitoring terminal 1-1-1 and the monitoring terminal 1-1, the monitoring terminal 1, the concentrator and the monitoring terminal 1-1-1 belong to the same branch network, and the concentrator, the monitoring terminal 1-1 and the monitoring terminal 1 are the superior equipment of the monitoring terminal 1-1-1.

3) When the monitoring terminal 1-1 performs branch recognition and sends pulse current, the concentrator and monitoring terminal 1 can receive the pulse current signal sent by the monitoring terminal 1-1. The same feature extraction method as in 1) is used to extract the pulse current signal communication address. Therefore, it can be determined that the monitoring terminal 1-1, the monitoring terminal 1 and the concentrator belong to the same branch network, and the concentrator and the monitoring terminal 1-1 are the superior equipment of the monitoring terminal 1-1.

4) When the monitoring terminal 1 performs branch recognition and sends pulse current, only the concentrator can receive the pulse current signal sent by the monitoring terminal 1. The same feature extraction method as in 1) is used to extract the pulse current signal communication address. Therefore, it can be determined that the monitoring terminal 1 and the concentrator belong to the same branch network, and the concentrator is the superior equipment of the monitoring terminal 1.

5) By analogy, the attribution relationship of all nodes can be analyzed, and the recognition result of the physical topology relationship of the entire network can be obtained, which is denoted as $Z_1$.

After the topology recognition result $Z_1$ of the entire distribution area is obtained, the topology recognition check is performed using the charge space-time feature method based on edge computing. If the relationship between the nodes meets the charge space requirements, the topology recognition result passes the comparison test. Otherwise, the recognition result fails, and the topology relation needs to be re-recognized through the topology recognition method based on the pulse current signal. By analogy, the corresponding charge relationship model is established and verified for all nodes in the topology recognition result $Z_1$. If the requirements are met, the topology recognition result $Z_1$ is uploaded to the master station system, so that the low-voltage distribution area topology network can be plotted.

5.3. System implementation and verification

Use the method described herein to develop an intelligent monitoring terminal and install it in a test bench area. The on-site installation is shown in Figure 8.
Figure 8. Installation relationship diagram of monitoring terminal in a low-voltage distribution area

Combine the pulse current-based hardware recognition method with the software-based pulse current time-frequency feature extraction method to identify the distribution area topology. The topology recognition management system can monitor the operation of the entire distribution area as well as information such as line loss and topology recognition relationship in real time.

The topology recognition system based on monitoring terminal can not only achieve automatic formation, automatic update and automatic maintenance of the topology, but also accurately plot the topological map of the low-voltage distribution area. The monitoring terminal can also support calculation of hourly line loss, implement layered and hierarchical calculation of line loss. It can calculate the line loss between the master meter and the branch of the distribution area, the line loss between the branch and the meter box, the line loss between the branch and the household meter, as well as the line loss between the meter box and the household meter. Also, it is possible to quickly and accurately locate the abnormal location with line loss, which lays a solid foundation for the establishment of an intelligent monitoring system in the low-voltage distribution area.

The system is applied to a demonstration distribution area in Dalian, and topology recognition is performed on the household meter and branch boxes of 159 resident users. The accuracy rate reaches 100%, which meets the technical requirements. The system monitoring effect is shown in Figure 9.

Figure 9. The topology identification effect diagram for low-voltage distribution areas
6. Conclusion
This paper combined the hardware recognition method based on pulse current communication and the software recognition method based on time-frequency feature extraction to develop a new type of intelligent monitoring terminal. It can provide strong support for the fine management of the low-voltage distribution area. To improve the topology recognition accuracy, the charge space-time feature method based on edge computing was used to verify the topology recognition results. The corresponding charge relationship model was established based on all nodes in the test bench area, which is verified using the charge space-time features. By installing monitoring terminal in the multi-level branch box and meter box distribution area, the automatic formation, automatic update and automatic maintenance of the low-voltage distribution area topology were achieved. In addition, the low-voltage distribution area monitoring system using this monitoring terminal can support automatic calculation of line losses at all levels, automatic fault diagnosis and automatic clarification of distribution area files. Field application results show that by using this monitoring terminal, it is possible to effectively enable household meter identification and line loss measurement in the distribution area, which carries important application significance for establishing unified lean management and control of the low-voltage distribution area. In the future, we should further improve recognition accuracy and recognition efficiency, so that it will play a greater role in delicacy management of distribution areas.

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