

Optimal Coordination of Directional Overcurrent Protection Relays Using Genetic Algorithm

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ABSTRACT

This paper studies on establishing the mathematical optimization formulation to coordinate the operating times of directional overcurrent relays in transmission networks. The objective function of this optimization formulation is to minimize the total operation time of all directional overcurrent relays, and it must satisfy the highly nonlinear constraints such as the time multiplier setting range, the plug setting range, and the coordination time interval between the primary and backup relay pair. The optimal variables consist of the time multiplier setting and the plug setting which are determined by applying the genetic algorithm on MATLAB software. This optimization formulation is evaluated and validated via the simulation results of the test systems including the 4-bus network and 9-bus network. These test systems are modeled and simulated by using PowerWorld software to calculate the power flow results in the steady state and the short-circuit currents flowing the primary/backup relay pair. The simulation results confirm that the operating time coordination of directional overcurrent relays is capable of meeting the requirements of a relay protection system, improving the reliability of power system.

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1. Introduction

The relay protection systems play a vital role in ensuring the power system security and stability, especially the power grids integrated with distributed generations and microgrids. The traditional relays with fixed settings have some difficulties in many different operating conditions, therefore, the adaptive relay protection systems become a necessary issue. Nowadays, digital overcurrent relays enable to make new protection methods, improving the selectivity, sensitivity, and reliability of the systems. The adaptive protection helps to detect and isolate rapidly, responding the strict requirements of modern power systems [1].

Directional protection relays are important devices in power systems with main functions of determining the short-circuit current direction, they will then isolate the faulty sections rapidly and correctly. The directional overcurrent protection relays help to enhance the sensitivity and speed of the protection system, especially in complex power systems integrated with distributed generations. The published works proposed many directional overcurrent relay time coordination to optimize the relay operation times and mitigate mis-operation actions of the protection system [2], [3], [4]. Furthermore, the standard characteristics of digital relays are also considered and evaluated to respond modern power system requirements [5].

The adaptive directional overcurrent relay protection method automatically adjusts the settings based on the transmission network configuration changes and operation conditions [6]. This method helps to enhance the sensitivity and overcome the distributed generation faults in smart grids [7]. The optimization methods such as the particle swarm optimization, search box optimization and improved heap-based algorithm were used to optimize the coordination time between the directional overcurrent relays and distance relays [8], [9], [10]. These methods confirmed that they were effective in smart grids and microgrids [11], [12].

The optimization methods for coordinating the directional overcurrent relay operation times help to improve the power system effectiveness and reliability. In the published work [13], the adaptive fuzzy directional bat algorithm was proposed to optimize the directional overcurrent relay coordination times, while the authors in the published work [14] developed an improved firefly algorithm for the optimal coordination of directional overcurrent relays. The Harris hawk optimization was applied to optimize the operating coordination of numerical and directional overcurrent relays in complex power systems [15], and non-standard characteristics help to protect temporary faults correctly [16], [17].

The neural networks have been applied to enhance the function of directional overcurrent relays in complex power systems. The radial basis function neural networks automatically adjusted the relay settings consisting of the time multiplier setting (TMS) and the plug setting (PS) for the transmission networks integrated with distributed generations, improving the operating coordination effectiveness [18]. Additionally, the artificial neural networks optimize the operation times of directional overcurrent relays, reducing the protection relay mis-synchronization in complicated networks [19].

The research works about adaptive directional overcurrent protection methods in modern transmission networks created a background for developing effective protection techniques, especially complicated networks and smart grids. The adaptive protection systems enable to optimize the relay settings, ensuring the power system flexibility for the critical operating conditions such as distributed generation variations or operation mode changes. This system emphasized the necessity of optimal relay coordination to response the operating conditions changed continuously, enhancing the relay protection system reliability and capability. The approaches research on coordinating the directional overcurrent relay operation times by using the optimization techniques, making a significant effectiveness in protective capability improvement and power system stability. These approaches improve especially the protective effectiveness in specified conditions, and strengthen the protection system flexibility and responsibility during abnormal conditions in power systems [20].

However, the aforementioned methods have still existed some disadvantages. Firstly, the adaptive relay settings in real time have still not completed, especially for rapid and complicated change of transmission networks nowadays [21]. This leads to synchronization loss of the protection system when the fault current varies unevenly. Secondly, the adaptive protection solutions for power systems integrated with distributed generations still depend highly on simulation results rather than practical experiments. This issue causes some limitations of feasibility as applying the methods in practical networks, the protective effectiveness cannot thereby be verified fully [22]. Finally, the directional overcurrent relay protection system has some difficulties as adjusting the relay settings, especially the significant change in the fault current magnitude and direction caused by the distributed generations. These changes can lead to lost a synchronization and create a negative impact on the power system stability, thus the adaptive coordination optimization methods need to be developed in practical transmission networks [23], [24].

This paper proposes a new method of the operation coordination of directional overcurrent protection system for complex power system integrated with renewable energy sources. This method uses the genetic algorithm (GA) to optimize the relay settings consisting of the time multiplier setting (TMS) and the plug setting (PS) as having the configuration changes and operation conditions of the power system. This way helps to improve the flexibility, and it ensures that the power system responds quickly and effectively for the faults, optimizes the fault detection and isolation time to minimize the negative impact on the power system. The proposed method enhances the fault detection accuracy, reducing the directional overcurrent relay mis-operation and economic damage for the power system. Finally, this paper also contributes to build the background for smart protection relays with automatic technologies and artificial neural networks.

2. Mathematical Optimization Formulation

The main issue is to ensure the selectivity, sensitivity, reliability of the protection system in fault conditions. The coordination time of directional overcurrent relays is optimized in this paper, however, it must satisfy the correct coordination between the relays to operate the power system safely and effectively. This paper establishes the mathematical optimization formulation based on the following equations.

2.1. Objective function

The objective function of this problem is to minimize the total operation time of all directional overcurrent protection relays when a fault occurs on the power system as follows:

$$\text{Minimize } \sum_{i=1}^n t_i \quad (1)$$

where t_i is the operation time of the i^{th} relay; n is the total number of relays.

The relay operation time is determined according to the characteristic curves defined the IEC/IEEE standard:

$$t_i = \frac{A \times TMS_i}{\left(\frac{I_{Fi}}{PS_i}\right)^B - 1} \quad (2)$$

where A and B are the constants depending on the characteristic curve type of the relay; I_{Fi} is the fault current through the i^{th} relay; TMS_i and PS_i is time multiplier setting (TMS) and the plug setting (PS) of the i^{th} relay, respectively. For the inverse-time characteristic curve according to the IEC/IEEE standard, the constants are $A = 0.14$ and $B = 0.02$.

2.2. Constraint 1: Operation time coordination between primary and backup relays

To ensure mis-operation issues, the operation time coordination between the primary and backup relays must satisfy the constraint in Equation (3). This paper sets the backup time interval $\Delta t = 0.2$ seconds [27]. In Equation (3), the backup time interval represents the backup time between the primary and backup relays to ensure the selectivity of the relay protection system.

$$t'_j - t_i \geq \Delta t \quad (3)$$

where t_i is the operation time of the i^{th} primary relay; t'_j is the operation time of the j^{th} backup relay.

2.3. Constraint 2: Time multiplier setting range

Equation (4) can be used to determine the minimum and maximum time multiplier settings of the i^{th} relay. The time multiplier setting of the i^{th} relay (TMS_i) must be within the range from TMS_i^{min} to TMS_i^{max} . In this paper, this range is established by $TMS_i^{\text{min}} = 0.01$ seconds and $TMS_i^{\text{max}} = 1.1$ seconds [28]. The appropriate choice of TMS settings will provide grading of a network protection system.

$$TMS_i^{\text{min}} \leq TMS_i \leq TMS_i^{\text{max}} \quad (4)$$

2.4. Constraint 3: Plug setting range

The plug setting of the i^{th} relay (PS_i) is also determined in the range from the minimum plug setting (PS_i^{min}) to the maximum plug setting (PS_i^{max}) as Equation (5):

$$PS_i^{\text{min}} \leq PS_i \leq PS_i^{\text{max}} \quad (5)$$

The minimum plug setting (PS_i^{min}) is usually greater than or equal to the maximum normal current rating (I_{OL}^{max}) to ensure that the protection relay will operate for the overload cases as follows:

$$I_{OL}^{\text{max}} = K \times I_L^{\text{max}} \quad (6)$$

where I_L^{max} is the maximum normal current rating through the relay; K is the overload factor which usually ranges between 1.25 and 1.5.

The maximum plug setting (PS_i^{max}) is usually less than or equal to the minimum fault current rating (I_F^{min}) through the relay when a fault occurs at the end of the protected element by the relay as follows:

$$PS_i^{max} = \frac{2}{3} I_F^{min} \quad (7)$$

2.5. Constraint 4: Operation time range

The operation time range of the i^{th} relay is determined by Equation (8):

$$t_i^{min} \leq t_i \leq t_i^{max} \quad (8)$$

The directional overcurrent relays trip the circuit breaker based on the inverse-time characteristic curve, in which the operation time depends on the time multiplier setting (TMS) and the plug setting (PS), defined in Equation (2). The relay operation time is inversely proportional to the fault current rating: the fault current rating increases, the relay operation time will be decreased.

2.6. Genetic algorithm (GA)

In this paper, the genetic algorithm (GA) will be applied to solve the optimization problem in the directional overcurrent protection system on transmission networks, specifically for the 4-bus and 9-bus power systems. Using GA allows for the optimization of protection relay parameters such as the operation time and coordination sequence, ensuring that the protection system can adapt to the network structure changes [25]. For the 4-bus and 9-bus power systems, GA will solve to find the optimal parameter sets to minimize the response time, improve the protection system stability, and reduce the conflicts between the relays. Through simulation and analysis results on these two test systems, the optimization formulation will be solved, ensuring the selectivity, sensitivity, and effectiveness of the protection system under all operating conditions [26].

3. Simulation Results and Discussion

3.1. The 4-bus power system

In this section, a simplified 4-bus power system consists of two generators supplying power two loads as shown in Figure 1. The generator at bus 1 acts as a voltage-controlled source, supplying a 50-MW active power to the network and its reactive power varies in the acceptable limitation to regulate the bus-1 voltage at 1.00 pu. The generator at bus 4 acts as the balancing source in the power system, ensuring the active and reactive power balance and maintaining the frequency stability. The loads at bus 2 and bus 3 are $40 + j20$ MVA and $50 + j20$ MVA, respectively. The lines L1, L2, and L3 have the lengths of 50 km, 70 km, and 90 km, respectively. For the studying purpose of the directional overcurrent relay operation coordination, each line is equipped with two relays at both ends. The relay pair of R1 and R2 is used to mainly protect for the line L1, the relay pair of R3 and R4 is used to mainly protect for the line L2, and the relay pair of R5 and R6 is used to mainly protect for the line L3. Additionally, the positive operation direction for each relay is set by the direction from the bus towards the line.

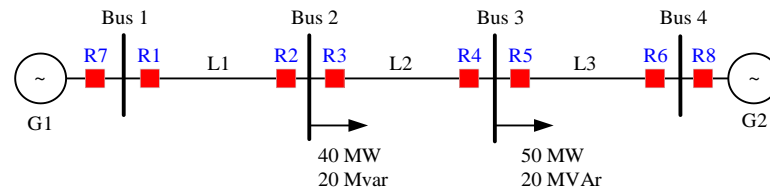


Figure 1. Single-line diagram of 4-bus power system

To determine the maximum current flowing through the relays, the steady state power flow of 4-bus power system is calculated in this case. Based on the simulation results using PowerWorld software, the normal operation current flowing through the relay pair of R1 and R2 is 272.40 A; the normal operation current flowing through the relay pair of R3 and R4 is 69.28 A, and the current through the relay pair of R5 and R6 is 266.63 A. These values will be used to establish the minimum plug setting of each relay

according to the constraint in Equation (5). Besides, to determine the maximum plug setting of each relay and the primary/backup relay pair for each transmission line, the authors have been sequentially performed three-phase short circuit faults at all nodes in the 4-bus power system. The first assumption is a three-phase short circuit occurring at the bus 1, the fault current will flow in the direction from the generator at the bus 4 through lines L3, L2, L1 to the bus 1. Therefore, the primary relay for the line L1 is the relay R2 and the backup relay for relay R2 is the relay R4. Another assumption is a three-phase short circuit occurring at the bus 2, the fault current will flow from the generator at the bus 1 through line L1 to the bus 2 and in the opposite direction the fault current will flow from the generator at the bus 4 through lines L3, L2 to the bus 2. Thus, the primary relay for the line L1 is the relay R1; the primary relay for the line L2 is the relay R4 and the backup relay for the relay R4 is the relay R6. In addition, the three-phase short circuit simulation results for the remaining buses in the 4-bus power system have been simulated and the obtained results are shown in Table 1.

Table 1. Fault current results for 4-bus power system

Fault location	Primary relay	Fault current (A)	Backup relay	Fault current (A)
Bus 1	R2	500.13	R4	523.53
Bus 2	R1	576.20		
	R4	600.92	R6	623.86
Bus 3	R3	512.77	R1	530.77
	R6	680.01		
Bus 4	R5	466.99	R3	478.70

Based on the results of power flow calculations under normal operation and three-phase short-circuit conditions at the buses in the 4-bus power system, the optimization problem for the time coordination of directional overcurrent relays in the system is established. The authors utilized then the Optimization Toolbox in MATLAB software by the GA using the following syntax:

$$[x, fval] = ga(ObjectiveFunction, nvars, [], [], [], [], lb, ub, ConstraintFunction)$$

In the above syntax, *ObjectiveFunction* is the objective function of the optimization problem, which is the total operation time of the six primary relays R1 to R6 in this case. *nvars* represents for the number of optimization variables: the time multipliers ($TMS_1, TMS_2, TMS_3, TMS_4, TMS_5, TMS_6$) and the plug settings ($PS_1, PS_2, PS_3, PS_4, PS_5, PS_6$); *lb* and *ub* are the lower and upper bounds of the optimization variables, respectively. *ConstraintFunction* refers to the constraints on the time multiplier and operation time ranges, as well as the plug setting limits for each relay. MATLAB 2024a software is used to execute the GA syntax, and the results are obtained as shown in Figure 2. The total operation time of the six primary relays is 2.129 seconds. Additionally, the operation time of each pair of primary and backup relays is illustrated in Figure 2(a), and the plug setting of each relay is presented in a bar chart as shown in Figure 2(b).

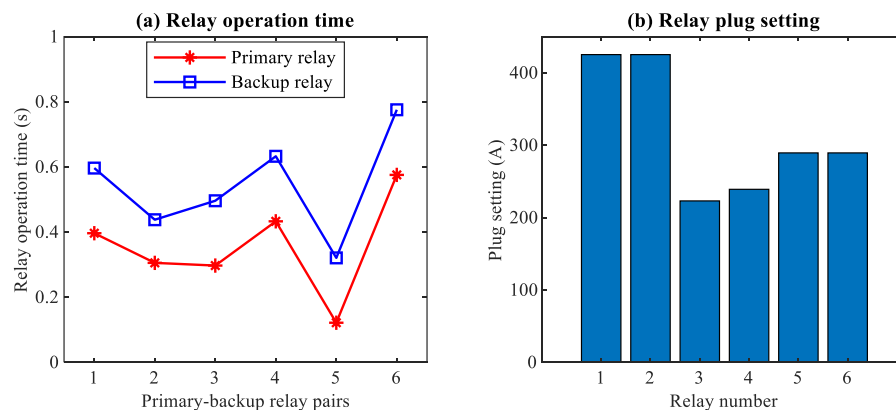


Figure 2. Optimal Coordination results for 4-bus power system

3.2. The 9-bus power system

The 9-bus power system consists of three generators at the buses 1, 2, 3 and three loads at the buses 5, 6, 8. The generator at the bus 1 acts as the slack bus in the system with the terminal voltage maintained at the constant of 1.04 pu. The generator at the bus 2 acts as a controlled-voltage source with the terminal voltage maintained at the constant of 1.04 pu and the 240.8-MW active power generating to network. The generator at the bus 3 also plays a controlled-voltage source with the terminal voltage maintained at the constant of 1.025 pu and the 85-MW active power generating to the network. The loads at the buses 5, 6 and 8 are 125 + j50 MVA, 90 + j30 MVA and 100 + j25 MVA, respectively. In addition, the power system consists of six 230-kV transmission lines, which are numbered from L1 to L6 and each line is protected by two directional overcurrent relays at both ends. All relays are numbered as shown in Figure 3.

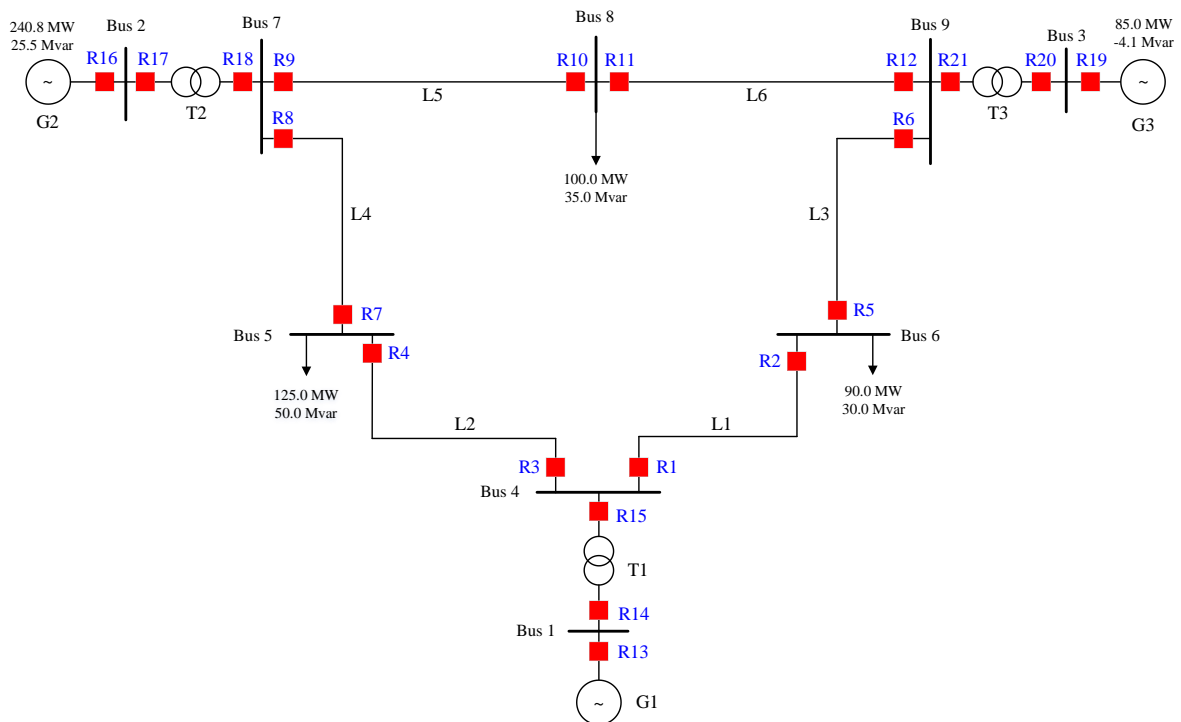


Figure 3. Single-line diagram of 9-bus power system

To determine the maximum normal current flowing through the relays, the authors run power flow for the 9-bus power system in the steady state mode. The normal current results flowing through the relays are shown in Table 2. These simulation results will be used to establish the plug setting current value of each relay according to the constraint (5). To identify the maximum plug setting for each relay and the primary/backup relay pair on the 9-bus power system, a three-phase short circuit fault is sequentially set at all buses in the system. It is assumed that a three-phase short circuit fault occurs at the bus 4, the fault current will flow from the generators 2 and 3 through the transmission lines L4, L3, L2, and L1 to the bus 4. Based on the obtained results, the primary/backup relay pair will be the primary relay R2, the backup relay R6 for line L1, the primary relay R4 and the backup relay R8 for line L2. Similarly, the fault locations are assumed that they are the other buses in the 9-bus power system to identify the primary/backup relay pair, as well as to determine the fault current flowing through these relays. The fault current simulation results flowing through the primary/backup relay pair are shown in Table 3.

Table 2. Normal current through the relays

Relay	Current (A)	Relay	Current (A)
R1	57.48	R7	366.87
R2	57.48	R8	366.87
R3	133.79	R9	75.06
R4	133.79	R10	75.06
R5	231.44	R11	268.09
R6	231.44	R12	268.09

Table 3. Fault current results for 9-bus power system

Location	Primary relay	Current (A)	Backup relay	Current (A)
Bus 4	R2	325.98	R6	319.97
	R4	443.8	R8	446.18
Bus 5	R3	930.38	R2	167.28
	R8	578.46	R10	
Bus 6	R1	861.77	R4	214.09
	R6	461.8	R11	220.47
Bus 7	R10	365.12	R12	374.32
	R7	451.98	R3	504.86
Bus 8	R9	832.48	R7	
	R12	469.74	R5	
Bus 9	R11	554.58	R9	572.19
	R5	427.19	R1	455.71

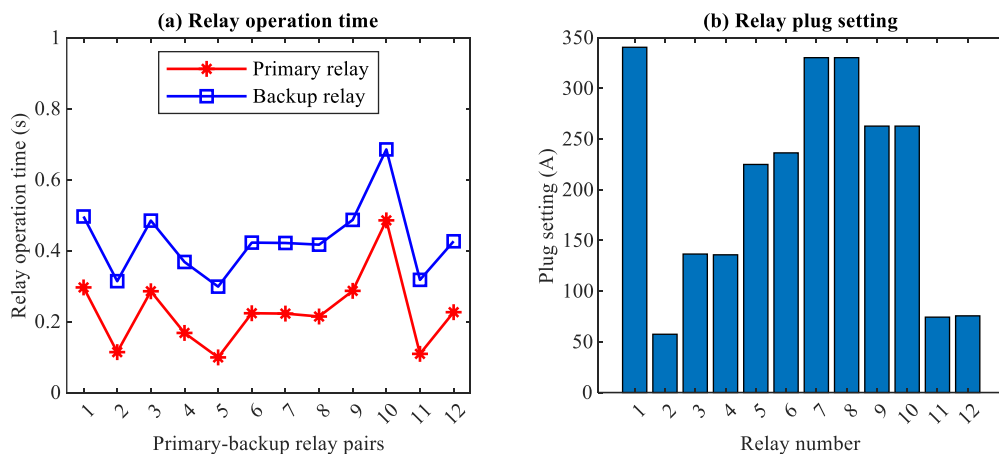


Figure 4. Optimal coordination results for 9-bus power system

For the coordination optimization problem of directional overcurrent relay protection in the 9-bus power system, *ObjectiveFunction* is the objective function of the total operation time of the 12 primary relays (form R1 to R12); *nvars* is the number of optimization variables such as the time multiplier settings (from TMS_1 to TMS_{12}), and the plug settings (from PS_1 to PS_{12}); *lb* and *ub* are the lower and

upper bounds of the optimization variables, respectively; *ConstraintFunction* represents for the constraints on the time multiplier setting range, the operation time range, and the plug setting limitation of each relay. MATLAB 2024a is also used to execute the GA command syntax, and the obtained results are shown in Figure 4. The total operation time of the 12 primary relays is 2.73 seconds. Additionally, the operation time of each pair of primary and backup relays is shown in Figure 4(a), and the plug setting of each relay is represented in the bar chart as shown in Figure 4(b).

4. Conclusions

This paper has developed an optimization method for the directional overcurrent relay operation coordination in transmission networks. The optimization problem is formulated with the objective function of minimizing the total operation time of all relays in the network, while it must satisfy the constraints of the time multiplier setting (TMS) range, the plug setting (PS) range, and the coordination time interval between the primary and backup relay pair. The genetic algorithm (GA) was applied to optimize the relay operation time coordination, ensuring that relays can respond promptly and accurately in short-circuit fault conditions in the network. The optimization problem is formulated in canonical form based on the function syntax in the Optimization Toolbox in MATLAB to solve this optimization problem. The research results for the 4-bus and 9-bus power systems have been simulated and verified in this paper, showing the optimal coordination among the relays in the system. The research method in this paper can be extended to apply to larger and more complex power systems. Based on the results obtained from the paper, the next research direction is to integrate fault location methods on the transmission lines to optimize the decision variables in the established optimization formulation. This will create an adaptive protection system by automatically adjusting the setting parameters of directional overcurrent relays.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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