

Adaptive Short-Circuit Current Calculation Model based on Colored Petri Net

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Abstract

According to structural characteristics of the coal mine high-voltage grid, we propose an adaptive short-circuit current calculation model based on colored Petri net that includes a network topology self-learning model and a calculation model. The former model includes 10 places and 7 transitions, and the latter model includes 5 places and 4 transitions. According to coding results of the network topology self-learning model, we set the initial state of place information. Then, according to the rules of transitional trigger, the calculation model can complete adaptive short-circuit current calculation of some output switch. Simulation results show that the model can effectively learn the topology relationship of power grid and achieve adaptive short-circuit current calculation of coal mine high-voltage grid. Meanwhile, compared to the adaptive short-circuit calculation algorithm based on the state of interconnection switch, the adaptive short-circuit calculation model based on colored Petri Net can shorten the time needed to complete the short-circuit calculation. Furthermore, when the number of output switch is 72, the time overhead of short-circuit calculation is about 20 times as much as the time overhead in short-circuit calculation algorithm based on the state of interconnection switch.

Keywords: adaptive short-circuit calculation; topology self-learning; coal mine high-voltage grid; colored Petri net

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1. Introduction

Relay protection is one of the foremost secondary systems in power system, which plays a very important role in the safe and steady operation for power systems. So, relay protection setting calculation is essential in the generation of electricity. Short-circuit current calculation will affect the relay protection setting values and is the basis of checking protective action in different system conditions [12]. There are mainly two steps to complete the short-circuit current calculation. The first step is to complete the self-learning of network topology, and the second step is to calculate corresponding short-circuit current based on the topology self-learning result.

The literatures [3,4] have put forward an algorithm of short-circuit current with a variable structure model that can calculate relay protection setting easier. When the distributed generation accesses the distribution networks, it changes the single radicalized structure of distribution networks, causing mal-operation or non-operation of relay protection. In order to solve this problem, the literatures [6,9] give a universal method about short-circuit calculation when distributed generation accesses. The literatures [1,2] build models of distribution networks that contain distributed generation and put forward an adaptive short-circuit algorithm when the accessing position is different. The literature [5] proposes a short-circuit current computation method for electric elements with a converter. The approximate analytic expression of transient is obtained by calculation, which lays the foundation for relay protection setting calculation. The literatures [10,11] propose a short-circuit current calculation method of distribution network with distributed generation. When short circuit occurs in a distribution network, the short circuit current is obtained under different short circuit types through the equivalent model of distributed generation.

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When the above-mentioned literatures complete network topology self-learning for the power system, they usually use a breadth-first or depth-first search algorithm, but the searching efficiency is relatively lower. Meanwhile, because the coal mine high-voltage grid belongs to single power open grid, the above-mentioned short-circuit current calculating methods cannot directly apply to the coal mine high-voltage grid. The literature [7] proposes a mathematical model for automatic short-circuit calculation based on incidence matrix in a coal mine high-voltage grid. It can achieve the short-circuit calculation of coal mine high-voltage grid in default running mode. However, when the running mode of high-voltage grid changes, it will not be able to achieve the short-circuit calculation. To solve this problem, the literature [8] proposes an adaptive short-circuit calculation algorithm based on the state of interconnection switch. It can achieve the adaptive short-circuit calculation regardless of whether the running mode changes. However, its time complexity is too high.

In order to achieve the adaptive short-circuit calculation and lessen the time complexity, this paper puts forward an adaptive short-circuit calculation model based on colored Petri net. It can quickly complete network topology self-learning as well as the coding of equipment nodes aimed at coal mine high-voltage grid under different operation modes. It can also realize the adaptive short-circuit current calculation.

2. Adaptive short-circuit current calculation model based on colored Petri net

2.1. Network topology self-learning model based on colored Petri net

Network topology self-learning model is as follow in Figure 1. In this model, the place S_1 stores coded power input switch information; the place S_2 stores uncoded output switch information; the place S_3 stores coded output switch information adjacent to the power input switch; the place S_4 stores coded output switch information adjacent to the place S_3 ; the place S_5 stores coded output switch information; the place S_6 stores other uncoded input switch information; the place S_7 stores coded output switch and coded input switch information; the place S_8 stores coded input switch information; the place S_9 stores uncoded interconnection switch information; the place S_{10} stores coded interconnection switch information.

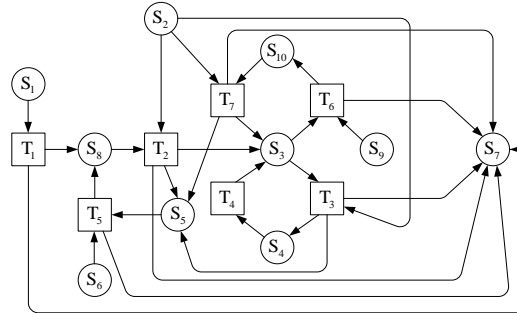


Figure 1. Model of network topology self-learning

In the network topology self-learning model, this paper defines switch type color as monochrome, expressed as γ . γ is a positive integer, $\gamma=1$ represents power input switch, $\gamma=2$ represents output switch, $\gamma=3$ represents interconnection switch, $\gamma=4$ represents general input switch. We define switch position color as composite color. If a basic unit has n nodes $E_1, E_2, E_3, \dots, E_n$ and m switches $X_1, X_2, X_3, \dots, X_m$, the switch position composite color is expressed as $X_m = \langle E_i, E_j, \dots, E_n \rangle$. We define switch state color as monochrome, expressed as w . w is positive integer, $w=0$ represents opening, $w=1$ represents closing. We define switch coding color as composite color, expressed as $Z = \langle Z_1, Z_2, Z_3 \rangle$, inside Z_1 represents the coding of switch, Z_2 represents switch serial number in one level. This paper defines serial number from 1 to 50, Z_3 represents the number of level. The switch composite color of high-voltage switch is $\langle \langle E_i, E_j, \dots, E_n \rangle, \gamma, w, \langle Z_1, Z_2, Z_3 \rangle \rangle$, expressed as $\langle \langle E_i, E_j, \dots, E_n \rangle, \gamma, w, \langle Z_1, Z_2, Z_3 \rangle \rangle$.

1) Adjacent rule of switches

For two switches $X_a = [E_{i1}, E_{i2}, \dots, E_{in}]$ and $X_b = [E_{j1}, E_{j2}, \dots, E_{jm}]$, $m, n \geq 2$. If there exists $P_{ri} X_a = P_{rj} X_b$, the switches X_a

and χ_b are adjacent, and P_{ri} represents the i^{th} color or element of composite color or collection, p_{rj} represents the j^{th} color or element of composite color or collection.

In this model, assuming that the switch composite color of token in place $S_1 \sim S_{10}$ is respectively expressed as a 、 b 、 c 、 d 、 e 、 f 、 g 、 h 、 k and l . According to the diagram of coal mine high-voltage grid, set the initial identification of place S_1 、 S_2 、 S_6 and S_9 , and according to the ignition rules of transition that the network topological analysis model defines, it finishes the topological analysis of the diagram of the coal mine high-voltage grid and completes the topological coding for every high-voltage switch. When transition T_3 and T_6 clash, it determines whether there are interconnection switches in this level. If there are and it is opening ($P_{r3}k = 0$), execute transition T_3 ; if there are interconnection switches and it is closing ($P_{r3}k = 1$), the transition T_3 has priority to ignite. If the transition T_3 does not ignite, then execute transition T_6 .

2) Ignition rule of transition T_1

If tokens exist in place S_1 , the transition T_1 ignites and the place S_1 will consume a token after igniting. Add the token of the encoded power input switch that place S_1 consumed to the place S_8 and S_7 respectively; so, $P_{r1}g = P_{r1}a$, $P_{r1}h = P_{r1}a$ ($1 \leq i \leq 4$).

3) Ignition rule of transition T_2

If there exist tokens in place S_8 and place S_2 , according to adjacent rule of switches, the two corresponding switches of place S_8 and place S_2 are adjacent, and $P_{r3}b = 1$, the transition T_2 ignites. The places S_2 and S_8 will consume a token respectively after igniting, aiming at the token that place S_2 consumed. This paper will code according to the coding rules, adding the token that has encoded the places S_3 、 S_5 and S_7 respectively, assuming that $P_{r4}h = \langle Z_1, Z_2, Z_3 \rangle$, so $P_{r1}c = P_{r1}b$, $P_{r2}c = P_{r2}b$, $P_{r3}c = P_{r3}b$, $P_{r4}c = \langle 1 \times 50^{Z_3+1} + Z_1, 1, Z_3 + 1 \rangle$, $P_{r1}e = P_{r1}c$, $P_{r2}e = P_{r2}c$, $P_{r3}e = P_{r3}c$, $P_{r4}e = \langle 1 \times 50^{Z_3+1} + Z_1, 1, Z_3 + 1 \rangle$, $P_{r1}g = P_{r1}b$, $P_{r2}g = P_{r2}b$, $P_{r3}g = P_{r3}b$, $P_{r4}g = \langle 1 \times 50^{Z_3+1} + Z_1, 1, Z_3 + 1 \rangle$.

4) Ignition rule of transition T_3

If there exist tokens in place S_3 and place S_2 , according to adjacent rule of switches, the two corresponding switches of place S_3 and place S_2 are adjacent, and $P_{r3}b = 1$. The transition T_3 ignites, the place S_2 and S_3 will consume a token respectively after igniting, aiming at the token that place S_2 consumed. This paper will code according to the coding rules, adding the token that has encoded to the place S_4 、 S_5 and S_7 respectively, assuming that $P_{r4}c = \langle Z_1, Z_2, Z_3 \rangle$, so $P_{r1}d = P_{r1}b$, $P_{r2}d = P_{r2}b$, $P_{r3}d = P_{r3}b$, $P_{r4}d = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$, $P_{r1}e = P_{r1}b$, $P_{r2}e = P_{r2}b$, $P_{r3}e = P_{r3}b$, $P_{r4}e = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$, $P_{r1}g = P_{r1}b$, $P_{r2}g = P_{r2}b$, $P_{r3}g = P_{r3}b$, $P_{r4}g = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$.

5) Ignition rule of transition T_4

If there exist tokens in place S_4 , the transition T_4 ignites, the place S_4 will consume a token after igniting, adding the encoded output switch token that place S_4 consumed to place S_3 . So $P_{r1}c = P_{r1}d$ ($1 \leq i \leq 4$).

6) Ignition rule of transition T_5

If there exist tokens in place S_5 and place S_6 , according to adjacent rule of switches, the two corresponding switches of place S_5 and place S_6 are adjacent, and $P_{r3}f = 1$. The transition T_5 ignites, the place S_5 and S_6 will consume a token respectively after igniting, aiming at the token that place S_6 consumed. This paper will code according to the coding rules,

adding the token that has encoded to the place S_7 and S_8 respectively, assuming that $P_{r3}e = \langle Z_1, Z_2, Z_3 \rangle$, so $P_{r1}g = P_{r1}f$, $P_{r2}g = P_{r2}f$, $P_{r3}g = P_{r3}f$, $P_{r4}g = \langle 1 \times 50^{Z_3+1} + Z_1, 1, Z_3 + 1 \rangle$, $P_{r1}h = P_{r1}f$, $P_{r2}h = P_{r2}f$, $P_{r3}h = P_{r3}f$, $P_{r4}h = \langle 1 \times 50^{Z_3+1} + Z_1, 1, Z_3 + 1 \rangle$.

7) Ignition rule of transition T_6

If there exist tokens in place S_3 and place S_9 , according to adjacent rule of switches, the two corresponding switches of place S_3 and place S_9 are adjacent, and $P_{r3}k = 1$. The transition T_6 ignites, the place S_3 and S_9 will consume a token respectively after igniting, aiming at the token that place S_9 consumed. This paper will code according to the coding rules, adding the new token to the place S_{10} and S_5 , assuming that $P_{r4}c = \langle Z_1, Z_2, Z_3 \rangle$ and the added token in S_9 is expressed as kn , so $P_{r1}l = P_{r1}k$, $P_{r2}l = P_{r2}k$, $P_{r3}l = P_{r3}k$, $P_{r4}l = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$, $P_{ri}kn = P_{ri}k$, $1 \leq i \leq 4$.

8) Ignition rule of transition T_7

If there exist tokens in place S_{10} and place S_2 , according to adjacent rule of switches, the two corresponding switches of place S_{10} and place S_2 are adjacent, and $P_{r3}b = 1$. The transition T_7 ignites. The place S_{10} and S_2 will consume a token respectively after igniting, aiming at the token that place S_2 consumed. This paper will code according to the coding rules, adding the token that has encoded to the place S_3 , S_5 and S_7 . Assuming that $P_{r4}l = \langle Z_1, Z_2, Z_3 \rangle$, so $P_{r1}c = P_{r1}b$, $P_{r2}c = P_{r2}b$, $P_{r3}c = P_{r3}b$, $P_{r4}c = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$, $P_{r1}e = P_{r1}b$, $P_{r2}e = P_{r2}b$, $P_{r3}e = P_{r3}b$, $P_{r4}e = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$, $P_{r1}g = P_{r1}b$, $P_{r2}g = P_{r2}b$, $P_{r3}g = P_{r3}b$, $P_{r4}g = \langle 1 \times 50^{Z_3} + Z_1, Z_2 + 1, Z_3 \rangle$.

If the transition $T_1 \sim T_7$ cannot be triggered, topological encoding will complete, adding all encoded input switch tokens and output switch tokens to the place S_7 .

2.2. Calculation model based on colored Petri net

In this model, the place S_{11} stores all coded output switch and coded power input switch information. In the original state, the place S_{12} stores the information of output switch that needs to complete short-circuit current calculation; the place S_{13} stores output switch information that has completed calculation of impedance; the place S_{14} stores the information of output switch that has completed three-phase short-circuit current calculation; the place S_{15} stores the information of output switch that has completed two-phase short-circuit current calculation. Figure 2 is a model of the short-circuit current calculation.

The calculation model defines switch coding color as composite color; defines switch type color as monochrome; defines impedance color as composite color. It is expressed as $\langle res, \max rea, \min rea \rangle$, res represents the resistance color, $\max rea$ represents the reactance color in maximal running mode, and $\min rea$ represents the reactance color in minimum running mode. For the output switch i , the initial value of impedance color is represented as $\langle res_i, \max rea_i, \min rea_i \rangle$, and res_i is the resistance of the line directly connected with output switch i . $\max rea_i$ and $\min rea_i$ are the reactance of the line directly connected with output switch i . For the power input switch j , the initial value of impedance color is represented as $\langle res_j, \max rea_j, \min rea_j \rangle$, and $res_j = 0$. $\max rea_j$ is the systematic reactance in maximal running mode and $\min rea_j$ is the systematic reactance in minimum running mode. We define short-circuit current color as composite color, which is expressed as $\langle threephase \text{ short-circuit current color}, twophase \text{ short-circuit current color} \rangle$. The initial value of short-circuit current color is $\langle 0, 0 \rangle$. So, the short-circuit current calculation color is $\langle switch \text{ type color}, switch \text{ coding color}, impedance \text{ color}, short-circuit current color} \rangle$.

The model of short-circuit current calculation is shown as Figure 2. In this model, assuming that short-circuit current calculation color of token in place $S_{11} \sim S_{15}$ is respectively expressed as p , q , o , u and v . Setting the initial identification of place S_{11} and S_{12} , according to the ignition rules of transition that the calculation model defines, it completes some output switch short-circuit current calculation.

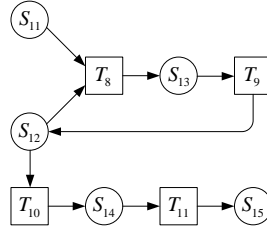


Figure 2. Model of short-circuit current calculation

1) Decision rules of supply relationship between the switches

Assuming that the coding of two switches is respectively represented as Z_{c1} and Z_{c2} , $Z_{c1} < Z_{c2}$, and “mod” function represents the operation of taking remainder.

For the switch whose coding is Z_{c1} , $r_m = \text{mod}(Z_{c1}, 50^{m+1})$, $x = \{r_0, r_1, r_2, \dots, r_m\}$. m represents the number of level, r_m represents the remainder of the relative level, and x represents the remainder set.

For the switch whose coding is Z_{c2} , $rc_n = \text{mod}(Z_{c2}, 50^{n+1})$, $y = \{rc_0, rc_1, rc_2, \dots, rc_n\}$. n represents the number of levels, rc_n represents remainder of the relative level, and y represents the remainder set.

If $rc_i = r_i$ ($1 \leq i \leq m$, $m \leq n$), the switch whose coding is Z_{c2} is supplied with the switch whose coding is Z_{c1} . Otherwise, the switch whose coding is Z_{c1} or Z_{c2} does not have the supply relation.

2) Ignition rule of transition T_8

If the coding color of place S_{11} is expressed as Z_{c1} and the coding color of place S_{12} is expressed as Z_{c2} , according to decision rules of supply relationship between the switches, if the switch Z_{c2} is supplied with the switch Z_{c1} , the transition T_8 ignites. The place S_{11} will consume a token ($P_{r1}p = 1$ or $P_{r1}p = 2$) after igniting and the place S_{13} will create a new token, so $P_{r1}o = P_{r1}p$, $P_{r2}o = P_{r2}p$, $P_{r3r1}o = P_{r3r1}p + P_{r3r1}q$, $P_{r3r2}o = P_{r3r2}p + P_{r3r2}q$, $P_{r3r3}o = P_{r3r3}p + P_{r3r3}q$, $P_{r4}o = P_{r4}p$. When transition T_8 and T_{10} clash, transition T_8 has priority to ignite. If transition T_8 does not ignite, then it determines whether there exist tokens in place S_{12} or not. If it exists, the transition T_{10} will ignite.

3) Ignition rule of transition T_9

If there are tokens in place S_{13} , the transition T_9 ignites. The place S_{13} will consume a token after igniting, and then the place S_{12} will create a new token, so $P_{ri}q = P_{ri}o$ ($1 \leq i \leq 4$).

4) Ignition rule of transition T_{10}

The function of transition T_{10} is to complete three-phase short-circuit current calculation. The transition T_{10} ignites and passes the tokens of the place S_{12} to the place S_{14} , $P_{ri}u = P_{ri}q$, $i = 1, 2, 3$, three-phase short-circuit current calculated value is $P_{r4r1}u = I_{\max}^{(3)} = \frac{U}{\sqrt{3}\sqrt{P_{r3r1}q^2 + P_{r3r2}q^2}}$, $P_{r4r2}u = 0$. $I_{\max}^{(3)}$ is three-phase short-circuited current in maximal running mode; U is voltage of power supply system.

5) Ignition rule of transition T_{11}

The function of transition T_{11} is to complete two-phase short-circuit current calculation. The transition T_{11} ignites and passes the tokens of place S_{14} to place S_{15} , $P_{ri}v = P_{ri}u$, $i = 1, 2, 3$, two-phase short-circuit current calculated value is

$$P_{r4r1}v = P_{r4r1}u, \quad P_{r4r2}v = I_{\min}^{(2)} = \frac{U}{2\sqrt{P_{r3r1}u^2 + P_{r3r3}u^2}} \cdot I_{\min}^{(2)} \text{ is two-phase short-circuit current in minimum running mode.}$$

3. Model simulations

The coal mine high-voltage grid power supply system diagram is as Figure 3. It includes power input switches, output switches, other input switches, other output switches, and interconnection switches. In this paper, Figure 3 shows the power supply system diagram as an example and this paper simulates and analyses adaptive short-circuit calculation model based on colored Petri net of coal mine high-voltage power leakage protection. In the figure, the white represents closing and the black represents opening. The specific process is as follows:

3.1. Network topology self-learning model simulation

According to the network topology self-learning model, the network topology self-learning completes aiming at the coal mine high-voltage power supply system diagram in Figure 3. It then codes every switch, mastering power supply relationship between equipment. The model pre-configures the coding of power input switches. For X_1 , the switch coding is $Z_1 = 1$; for X_2 , the switch coding is $Z_1 = 2$. Other switches have not encoded and is expressed as $<0>$. The interconnection switch X_{19} is opening and the interconnection switch X_{20} is closing.

The power supply system diagram of coal mine high-voltage grid sets the initial identification of places S_1, S_2, S_6 , and S_9 . Under the initial state, other places do not have tokens. The initial state of network topology self-learning model identity diagram is shown in Figure 4.

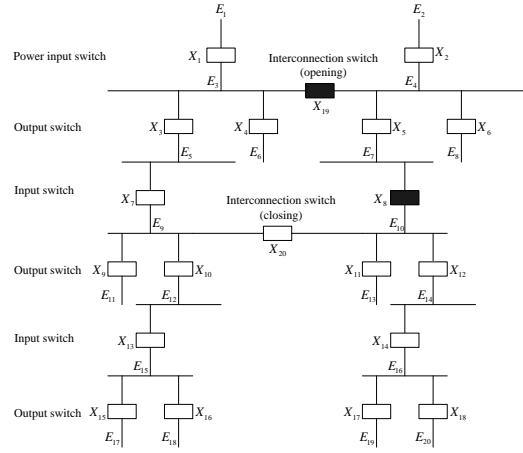


Figure 3. Coal mine high-voltage grid power supply system diagram

According to the activation conditions and priorities of the transitions in the network topology self-learning model, the transitions $T_1 \sim T_7$ are orderly executed. In the process, when transitions $T_1 \sim T_7$ cannot be triggered, topology encoding will be completed and all encoded input switch and encoded output switch information will be stored in the place S_7 . The final state of network topology self-learning model is shown in Figure 5.

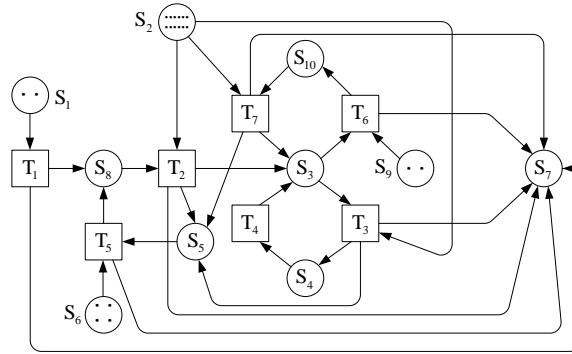


Figure 4. Initial state of network topology self-learning model identity diagram

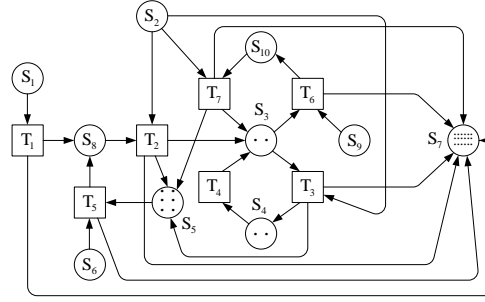


Figure 5. Final state of network topology self-learning model

Using CPN tools to parse structure characteristics of network topology self-learning model, the analysis mainly includes state space analysis, model accessibility, liveness and boundedness. It determines the accuracy and effectiveness of the model.

(1) Accessibility analysis

G^+ is a weight of arc from transition T_i to place S_i , G^- is a weight of arc from place S_i to transition T_i ; G^+ inputs incidence matrix, G^- is outputting incidence matrix, and $G = G^+ - G^-$. The relationship between identification vector M_0 and M can be described as $M = M_0 + G \cdot U$.

In this model, the initial identification vector $M_0 = [2 \ 12 \ 0 \ 0 \ 0 \ 4 \ 0 \ 0 \ 2 \ 0]^T$. According to simulations, the final identification vector $M = [0 \ 0 \ 5 \ 0 \ 9 \ 1 \ 18 \ 0 \ 1 \ 0]^T$. The inputting incidence matrix and outputting incidence matrix are respectively

$$G^+ = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^T, \quad G^- = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T.$$

So $U = [2 \ 5 \ 6 \ 6 \ 3 \ 1 \ 1]^T$. According to analysis of state space report on CPN Tools, under the initial identification M_0 , the transition firing sequence is $T_1 T_2 T_1 T_2 T_3 T_4 T_3 T_4 T_5 T_2 T_3 T_4 T_5 T_2 T_3 T_4 T_6 T_7 T_3 T_4 T_5 T_2 T_3 T_4$. The sequence is the same as $U(T_i)$, and according to the definition, the model has accessibility.

(2) Liveness analysis

The model is liveness, all state M_i is accessible from some transition, and it does not have a transition that will be able to perform.

3.2. Calculation model simulation

Based on the power supply system diagram of the coal mine high-voltage grid, according to the calculation model, this paper completes the short-circuit current calculation. If the output switch X_{17} needs to complete the short-circuit current calculation, it takes the short-circuit current calculation color of output switch X_{17} to the place S_{12} . So, the initial state identification diagram of the calculation model is shown in Figure 6. The initial identification setting of places S_{11} and S_{12} are as follows:

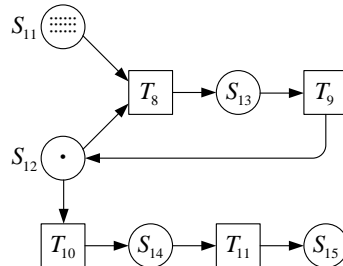


Figure 6. Initial state identification of short-circuit current setting diagram

According to the activation conditions and priorities of the transitions in the calculation model, it executes the transitions T_8 and T_9 repeatedly. In the process of repeating, when transitions T_8 and T_9 cannot be triggered, it completes the impedance calculation. After completing the impedance calculation, it orderly executes the transitions T_{10} and T_{11} and short-circuit current calculation will be completed. The final state of calculation model is shown in Figure 7.

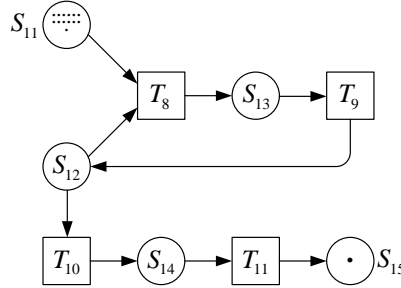


Figure 7. State identification diagram after completing short-circuit current calculation

After completing short-circuit current calculation of output switch X_{17} , the final place S_{15} has a token:

$$M(S_{15}) = \langle 2, \langle 1 \times 50^5 + 1 \times 50^4 + 5 \times 50^3 + 1 \times 50^2 + 1 \times 50 + 1 \rangle, \langle TR, TX_{\max}, TX_{\min} \rangle, \langle \frac{U}{\sqrt{3}\sqrt{TR^2 + TX_{\max}^2}}, \frac{U}{2\sqrt{TR^2 + TX_{\min}^2}} \rangle \rangle,$$

$$\text{and } TR = res_3 + res_{12} + res_{17}, \quad TX_{\max} = \max rea_1 + \max rea_3 + \max rea_{12} + \max rea_{17},$$

$$TX_{\min} = \min rea_1 + \min rea_3 + \min rea_{12} + \min rea_{17}.$$

The CPN tool is used to parse structure characteristics of the calculation model.

(1) Accessibility analysis

Aiming at the leakage protection setting calculation model, according to the definition above, the initial identification vector $M_0 = [18 \ 1 \ 0 \ 0 \ 0]^T$. According to simulations, the final identification vector $M = [13 \ 0 \ 0 \ 0 \ 1]^T$, and the inputting

incidence matrix and outputting incidence matrix are respectively as $G^+ = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T, G^- = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}^T.$

So, $U = [5 \ 5 \ 1 \ 1]^T$. According to analysis of state space report on CPN Tools, under the initial identification M_0 , transition firing sequence is $T_8 T_9 T_8 T_9 T_8 T_9 T_8 T_9 T_{10} T_{11}$. The sequence is the same as $U(T_i)$. According to the definition, the model has accessibility.

(2) Liveness analysis

The model is liveness, all state M_i is accessible from some transition, and it does not have a transition that is able to perform and deadlock phenomenon.

4. Performance comparison

The literature [8] proposes an adaptive short-circuit calculation algorithm based on the state of interconnection switch. In this model, it calculates the incidence N_p of bus node based on the incidence N_u 、 N_v of bus node and interconnection node. It then calculates the matrix G of supply relationship based on incidence matrix N_p 、 A and B . Finally, the adaptive short-circuit calculation is achieved on the basis of the matrix G . In the coal mine high-voltage grid, the number of interconnection switch is described as k , the number of input switch is described as m , and the number of output switch is described as n . The time complexity of adaptive short-circuit calculation algorithm in literature [12] is $O(3n^3 + mn^2 + 2n^2 + 2nm^2 + km^2)$, and when n is much greater than m and n is much greater than k , the time complexity is $O(n^3)$. This paper proposes the adaptive short-circuit current calculation model based on colored Petri net and its time complexity is $O(n^2)$. So, compared

with the literature [8], this paper can obtain a lower time complexity in the process of adaptive short-circuit calculation. However, in this algorithm more recursion will be used, and the time overhead of the recursion is relatively large. So, in order to better compare the consumed time overhead of the above two algorithms, the Visual C++ 6.0 is used to achieve the above two algorithms and obtain the time overhead of each algorithm. As shown in Figure 8 and Table 1, T_1 describes time overhead in the adaptive short-circuit current calculation model based on colored Petri net, T_2 describes time overhead in the adaptive short-circuit calculation algorithm based on the state of interconnection switch and $T_o = T_1 / T_2$. Assuming that $m = 4$ and $k = 2$, as shown in Figure 8 and Table 1, with the increase of the number n of output switch, the overhead T_2 is much larger than the time overhead T_1 , and when $n = 72$, adaptive short-circuit time overhead T_2 is about 20 times as much as T_1 . So, although the recursion adds an extra overhead in adaptive short-circuit mode based on colored Petri net, it still owns a faster speed of adaptive short-circuit compared with the literature [8].

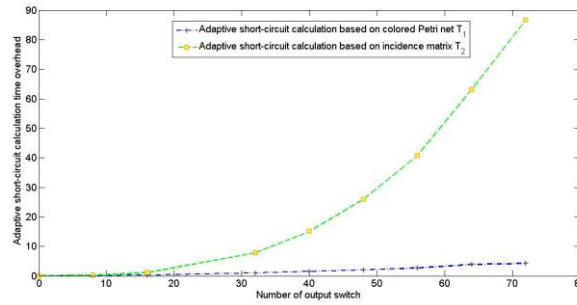


Figure 8. Adaptive short-circuit calculation time overhead

Table 1. Adaptive short-circuit calculation time overhead

n	8	16	32	40	48	56	64	72
T_1 (ms)	0.141	0.328	0.985	1.5	2.031	2.672	3.9	4.2
T_2 (ms)	0.188	1.109	7.844	15.063	25.906	40.78	63.13	86.57
T_o (ms)	1.33	3.38	7.96	10.04	12.76	15.26	16.19	20.61

5. Conclusions

According to structure characteristics of coal mine high-voltage grid, this paper proposes an adaptive short-circuit current calculation model based on colored Petri net. At first, by means of network topology self-learning model based on colored Petri net, it completes network topology encoding and accesses the relationship between high-voltage switches. Then, according to coding results of the network topology self-learning model and the rules of transitional trigger, it completes short-circuit current calculation of some output switch. Simulation results show that the model has the characteristics of simplicity, fast inference and wide universality. Meantime, compared with adaptive short-circuit calculation algorithm based on the state of interconnection switch, the adaptive short-circuit calculation model based on colored Petri Net can achieve the short-circuit calculation with less time. When the number of output switch is 72, its time overhead is about 20 times as much as the time overhead in the short-circuit calculation algorithm based on the state of interconnection switch.

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