Research on Tripping and Reclosing Strategy and Quasi-Three-Phase Operation of Double Circuit Lines on the Same Tower

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Abstract—Conventional protection of double-circuit lines on the same tower trip and reclose the two circuits independently after transmission line faults. The possibility of tripping all lines is high when inter-circuit faults occur. Large amount of load will be rejected and electrical link between two sides will be disconnected. It has negative effect on the stability of the power system. The paper proposes a novel tripping and reclosing strategy which regards the double circuits as a whole. It can decrease the possibility of tripping all lines and reclosing to permanent faults. According to the proposed strategy, the double circuits can transfer into the Quasi-Three-Phase Operation (QTPO) which remain at least one line of each phase after faults. The paper researches and analyses the feasibility of QTPO. A typical model of double circuit lines on the same tower is built in PSCAD/EMTDC. Some important electrical indexes which can reflect the performance of QTPO are analyzed by simulation. The results show that QTPO is feasible. The proposed scheme is benefit to the stability of system and satisfied the requirement of power industry operation.

Index Terms— Double circuit lines on the same tower; PSCAD/EMTDC; Quasi-Three-Phase operation (QTPO); tripping and reclosing.

I. INTRODUCTION

Double circuit lines on the same tower have been widely used in the UHV because of its lower cost than single lines. It can increase the reliability and capacity of the transmission line and reduce the occupied area [1-3]. It is important to improve the stability and reliability of the double circuit lines on the same tower [4-6].

Presently, the two circuits of double circuit lines are protected separately as two single transmission lines. For single transmission line, tripping and reclosing faulty lines is an effective method to clear transient faults. Automatic reclosure will be implemented after a fixed time delay. For transient faults, the dead time of reclosing is a challenge. If breakers reclose before the arc extinguishing of fault path, it will also threaten the stability of system [7-10]. If a permanent fault occurs, the operation of reclosing will aggravate the damage to the stability of system and the safety of apparatus. Many researches have been conducted on distinguishing whether the fault is transient or permanent and try to optimize reclosing strategy [11-13]. Wavelet transform can be used to obtain the secondary arc extinction time and detect permanent fault by artificial neural networks [14]. Arc voltage waveform can also be used to distinguish permanent fault [15]. Ref [16] proposes a scheme using the third harmonic of zero sequence voltage as criteria to distinguish transient and permanent faults. Using current of the shunt reactor, Ref [17] proposes a scheme to improve single phase reclosing scheme. Ref [18] proposes a reclosing scheme based on optimal control strategies to improve power-system dynamic behavior, however the calculation method is complex. Basing on the research of single line above, some reclosing schemes have also been implemented in double circuit lines [19-21]. However, due to the complex mutual inductance exist in double circuit lines, it is more difficult to distinguish permanent fault in double circuit lines on the same tower than single lines.

Considering the problems in existing strategies of double circuit lines, this paper proposed an improved strategy. It does not distinguish whether the faults are permanent or transient. The possibility of tripping faulty lines and reclosing to permanent faults can be reduced according to the strategy. It regards the two circuits as a whole. If the inter-circuit fault does not involve the two lines in the same phase, it is unnecessary to trip all lines in some situation. The number of fault types which two circuits might be tripped decrease from $10^4$ to 47. More transmission power can be maintained and reduce the amount of load which should be rejected. After faults, the double circuits can transfer into QTPO in most situations. QTPO is a type of non-all-line operation, in which each phase remains one line at least. Double circuits can operate in this mode for a period, enough time can be left for operators to transfer load
and deal with faults. For some types of faults which would trip all lines in conventional strategy, QTPO is a better choice because more transmission power and electric link between two sides can be kept. A typical double circuit lines on the same tower model is built in PSCAD/TMTDC to study the feasibility and performance of QTPO. The proposed scheme have been verified by simulation.

II. The Research of Novel Tripping and Reclosing Strategy

A typical double circuit lines on the same tower model is shown in Fig. 1.

![Model of typical double circuit lines on the same tower.](image)

In Fig. 1:
- Circuit 1 and circuit 2 are the transmission lines on the same tower.
- $E_M$ and $E_N$ are the source of M and N side, respectively.
- $T_M$ and $T_N$ are transformers of source M and N, respectively.

The double circuit lines were illustrated as circuit 1 and circuit 2. 1A, 1B and 1C represent the three phases of circuit 1, respectively. 2A, 2B and 2C represent the three phases of circuit 2, respectively. G represents a grounding fault. Take 1A2ACG as example, it represents the grounding fault involves 1A, 2A and 2C, here 1A and 2A are a pair of same-phase-lines. There are totally 120 types of single faults in double circuit lines, which can be divided into seven categories as shown in Fig. 2.

![Single-point fault classification of double-circuit transmission.](image)

### A. Novel tripping and reclosing strategy

In conventional tripping and reclosing strategy for most types of faults shown in Fig. 2, the protection will trip all faulty lines and then reclose. The paper proposes a novel strategy to decrease the operation of tripping and reclosing. It regards the double as a whole, making the double circuits transfer into the QTPO as far as possible. The improvements of the novel strategy can be made according to the two principles as follow:

1. Decrease the number of lines which should be tripped. For the whole double circuit lines on the same tower, when non-grounding faults include two lines in phase same, the two lines can be maintained. They are connected at same busbar at each side respectively and parameters of them are similar, little influence will be made when short circuit occurs between them. Only other faulty lines need to be tripped. Take non-grounding fault 1A2AB as example, the protection only need to trip 2B and then double circuits change into QTPO. While 1A and 2A can be kept to maintain more transmission power, this will benefit to the stability of system.

2. Decrease the number of lines which should be reclosed. For fault types which double circuits can be changed into QTPO by just tripping faulty lines, it is suggested to block the reclosure after faulty lines are tripped. Take the grounding fault 1A2BG as example, the protection only need to trip 1A and 2B. It can avoid continuing impact on the system if permanent fault occurs. For some fault types such as 1A2AG, one line should be reclosed after tripping to realize QTPO. However, for some fault types like 1AB2ABG, two line at least need to be reclosed, in this situation trip all lines and block the reclosure to decrease the possibility of reclosing to permanent faults.

In QTPO, the operators have enough time to transfer load and deal with faults. Based on the two principles above, the logic flow chart of the proposed tripping and reclosing strategy is shown in Fig. 3.

![flow chart of decision-making process.](image)

As shown in Fig. 3, after the occurrence of fault, whether it is a grounding fault is determined firstly. The strategy will be different according to the number of pairs of same-phase-lines involved.

For the grounding faults, the flow chart can be explained as follow:

- If more than one pairs of same-phase-lines are involved, trip all faulty lines and block reclosure. Such as 1AB2ABG, 1ABC2ABG.
- If one pair of same-phase-lines are involved, trip all faulty lines and reclose one line in the same-phase-lines. If the reclosure is successful, the double circuits can transfer into QTPO. Otherwise, trip all lines and block reclosure. Take 1AB2ACG as example, trip 1A, 1B, 2A, 2B and reclose 1A or 2A.
• If no same-phase-lines are involved, trip all faulty lines.

For the non-grounding faults, the flow char can be explained as follow:

• If no same-phase-lines are involved, keep one of faulty lines and trip the others.

• If one pair of same-phase-lines are involved, the same-phase-lines can be maintained and trip other faulty lines. Take 1AB2BC as example, just trip 1A and 2C can realize the QTPO.

• If two pairs of same-phase-lines are involved, take 1AB2ABC as example, two plans can be chosen to achieve the QTPO. Plan 1: maintain same-phase-lines in phase A, trip other faulty lines and reclose one line in phase B. Plan 2: maintain same-phase-lines in phase B, trip other faulty lines and reclose one line in phase A. If the reclosure is successful, the double circuits can transfer into QTPO. Otherwise, trip all lines and block reclosure.

• If three pairs of same-phase-lines are involved (all lines are involved), trip all lines and block the reclosure.

B. Comparison of the novel and conventional strategy

The conventional protection for double circuits in China regards them as two separate lines. Tripping and reclosing strategy can be expresses as:

• When single-phase-to-ground short circuits occur, trip the faulty line and then reclose. If reclosure fails, trip the fault circuit and block reclosure.

• When multi-phase short circuits occur in one circuit, trip the circuit and block reclosure.

• When inter-circuit faults occur in one circuit, trip and reclose, separately.

In conventional tripping and reclosing strategy, the only possible QTPO is one circuit operation (1ABC or 2ABC).

Considering the large number of short circuit types in double circuits, the comparison between optimal and conventional strategy in ten typical fault types is shown in Table 1.

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Faulty lines</th>
<th>Conventional strategy</th>
<th>Novel strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tripping</td>
<td>Reclosing</td>
<td>Tripping</td>
</tr>
<tr>
<td>1</td>
<td>1AB2AB</td>
<td>T6</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>1AB2AC</td>
<td>T6</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>1A2A</td>
<td>1A2A</td>
<td>1A2A</td>
</tr>
<tr>
<td>4</td>
<td>1A2BC</td>
<td>1A2A2B C</td>
<td>1A</td>
</tr>
<tr>
<td>5</td>
<td>1BC</td>
<td>1ABC</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>1AB2B2AG</td>
<td>T6</td>
<td>—</td>
</tr>
</tbody>
</table>

“T6”, “—”, “/” in Table 1 represent “tripping all transmission lines”, “no operation” and “or”, respectively. It can be seen that in given typical faults, the novel strategy reduces the types which all lines should be tripped. For other faults, the strategy can decrease the number of tripped lines. In this way, transmission power can be maintained as much as possible. The novel strategy also reduce reclosure lines and avoid reclosing to permanent faults to a great extent. The comparison of types of fault between conventional and novel strategy is shown in Table 2.

### TABLE II. CONTRAST OF TYPES OF FAULT BETWEEN CONVENTIONAL AND NOVEL STRATEGY

<table>
<thead>
<tr>
<th>Reclosing strategy</th>
<th>Number of fault type</th>
<th>The final operation state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do not reclose</td>
<td>16</td>
<td>QTPO</td>
</tr>
<tr>
<td>Reclose one line</td>
<td>54</td>
<td>Normal/QTPO/Trip All</td>
</tr>
<tr>
<td>Reclose multi-lines</td>
<td>18</td>
<td>Normal/QTPO/Trip All</td>
</tr>
<tr>
<td>Give up reclose</td>
<td>32</td>
<td>Trip All</td>
</tr>
</tbody>
</table>

As shown in Table 2:

• “Do not reclose” is applicable to the faults which can transfer into QTPO without reclosure. In conventional strategy, QTPO only includes one circuit operation. The fault types are multi-phase short circuits occur in one circuit and the other circuit operate normally such as 1ABG, 1ABC, et.al. Fault circuit will be tripped and block reclosure. “Do not reclose” can decrease the possibility of reclose to permanent faults in a great extent.

• “Reclose one line” is applicable to the faults which one line needed to be reclosed after tripping. In conventional, the fault types include single-phase-to-ground fault and inter-circuit faults such as 1AB2CG, 1ABC2G, and etc.

• “Reclose multi-lines” is applicable to the faults which multi-lines needed to be reclosed after tripping. In conventional, the fault types are inter-circuit faults which two lines are involved. Such as 1A2B, 1C2BG, and et.al. In novel strategy, this situation is not exist.

• “Give up reclose” is applicable to the faults which protection will trip all lines and block reclosure. In conventional, the fault types are inter-circuit faults which at least two lines are involved in each circuit. Such as 1AB2B2G, 1ABC2BC, and et.al. In novel
strategy, if multi-lines needed to be reclosed to transfer into QTPO, then “Give up reclose”.

Statistical result is shown in Table 2. The types of faults which “Do not reclose” increase from 16 to 73. So the possibility of reclosing to permanent faults is decreased. The total types of faults which might trip all lines decrease from 104 to 47. More power and the electric link between two sides can be maintained. It is benefit to the stability of the system. What is more, the switching number of breakers also can be decreased according to the proposed scheme. It can give a help to extend working life of breakers.

III. Research on the Feasibility of QTPO

As an operation mode, the performance of QTPO need to be researched. The paper study the feasibility of QTPO by simulation. A model of typical double circuit lines on the same tower is built in PSCAD/EMTDC. The structure of model is shown in Fig.1. According to simulation results, three electric indexes (over current rate, transmission power and unbalance degree) of QTPO are analyzed. Sources parameters are shown in Table 3.

The model of double circuits is based on the frequency dependent (phase) model. The length of transmission line is 150km. Considering the asymmetry of parameters in real condition, transmission lines will not ideally transposed. The space positions of double circuit lines are shown in Fig.4. The distance between transmission line and ground will increase because of the additional heat created by overcurrent. The temperature of these lines will decrease. It has negative effect on insulating property of transmission line. Temperature is a key factor which determines whether QTPO can be kept for a long time. Progress of temperature can be calculated according to [22]. Four typical QTPO are calculated as example. Relationship between line temperature and time has been researched. Fault types and fault current is shown in Table 4.

### Table III. Parameters of Sources in PSCAD/EMTDC

| Voltage of EM | 525kV |
| Voltage of EN | 500kV |
| ZM (equivalent impedance of M side) | (2+j18.84)Ω |
| ZN (equivalent impedance of N side) | (2+j18.84)Ω |

The model of double circuits is based on the frequency dependent (phase) model. The length of transmission line is 150km. Considering the asymmetry of parameters in real condition, transmission lines will not ideally transposed. The space positions of double circuit lines are shown in Fig.4.

![Fig. 4. Parameters of double circuit lines on the same tower.](image)

After tripping faulty lines, the load is transmitted to the other operating lines. The temperature of these lines will increase because of the additional heat created by overcurrent. The length of transmission lines will increase when temperature is high. The distance between transmission line and ground will decrease. It has negative effect on insulating property of transmission line. Temperature is a key factor which determines whether QTPO can be kept for a long time. Progress of temperature can be calculated according to [22]. Four typical QTPO are calculated as example. Relationship between line temperature and time has been researched. Fault types and fault current is shown in Table 4.

### Table IV. Current of Transmission Lines in QTPO

<table>
<thead>
<tr>
<th>Power angle</th>
<th>QTPOtype</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>Normal Operation</td>
<td>0.572 0.579 0.581 0.576 0.586 0.582</td>
</tr>
<tr>
<td></td>
<td>1ABC2A</td>
<td>0.554 0.542 0.514 0 0.833 0</td>
</tr>
<tr>
<td></td>
<td>1AB2BC</td>
<td>0.827 0 0.562 0.541 0 0.8</td>
</tr>
<tr>
<td></td>
<td>1AB2C</td>
<td>0.759 0 0 0.784 0 0.797</td>
</tr>
<tr>
<td></td>
<td>1ABC</td>
<td>0.758 0 0.805 0 0.8 0</td>
</tr>
<tr>
<td>20°</td>
<td>Normal Operation</td>
<td>0.748 0.758 0.759 0.752 0.765 0.761</td>
</tr>
<tr>
<td></td>
<td>1ABC2A</td>
<td>0.699 0.708 1.059 0 1.083 0</td>
</tr>
<tr>
<td></td>
<td>1AB2BC</td>
<td>1.061 0 0.754 0.707 0 1.041</td>
</tr>
<tr>
<td></td>
<td>1AB2C</td>
<td>0.888 0 1.021 0 0 1.086</td>
</tr>
<tr>
<td></td>
<td>1ABC</td>
<td>0.888 0 0.003 0 1.039 0</td>
</tr>
</tbody>
</table>

The temperature of transmission line when no faults occur can be calculated by the current of normal operation. According to the steady-state heat balance equation: [22]

\[ q_c + q_v = q_s + I^2R(T_c) \]  

(1)

Where \( q_c \) is converted heat loss rate per unit length, \( q_v \) is radiated heat loss rate per unit length, \( q_s \) is heat gain rate from sun. \( I \) is the largest current of six transmission lines. \( R(T_c) \) is the resistance of transmission line at temperature \( T_c \). If the speed of wind is low, \( q_c \) can be calculated as:

\[ q_c = [1.01 + 0.0372(0.057)][0.52]fK_{angle}(T_c - T_a) \]  

(2)

Where \( D \) is diameter of transmission line, \( \rho_f \) is the density of air, \( V_w \) is wind speed, \( \mu_f \) is dynamic viscosity of air, \( T_a \) is temperature of ambient air, \( T_{f,lim} \) is the mean temperature of \( T_c \) and \( T_a \), \( K_f \) is thermal conductivity of air at temperature \( T_{f,lim} \). \( K_{angle} \) is wind direction factor which can be expressed as:

\[ K_{angle} = 1.194 - \cos(\phi) + 0.194 \cos(2\phi) + 3.68 \sin(2\phi) \]  

(3)

Where \( \phi \) is angle between the wind direction and transmission line.

The radiated heat loss rate \( q_r \) can be expressed as:

\[ q_r = 0.0178De\left[\left(\frac{T_c + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right] \]  

(4)

Where \( e \) is the emissivity.

The solar heat gain \( q_s \) can be expressed as:

\[ q_s = \alpha Q_{se} \sin(\theta)A' \]  

(5)

Where \( \theta \) is effective angle of incidence of the Sun’s rays. \( A' \) is projected area of conductor per unit length. \( Q_{se} \) is total solar and sky radiated heat flux rate elevation corrected. \( \alpha \) is solar absorptivity.

According to (1)–(5), the temperature of transmission line in normal operation and QTPO can be calculated. The progress of temperature increasing can be expressed as:

\[ T_c(t) = T_i + (T_f - T_i)(1 - e^{-t/\tau}) \]  

(6)
\( \tau \) is the thermal time constant, it can be calculated as:

\[
\tau = \frac{(\bar{T} - T_C)mC_p}{R(T_C)(I_f^2 - I_i^2)}
\]

(7)

Where \( mC_p \) is total heat capacity of transmission line, \( T_C \) is temperature of transmission line prior to step increase, \( I_i \) initial current before QTPO, \( I_f \) is final current in QTPO.

In order to research the progress of temperature increase quantitatively, some conditions are assumed. Correlation parameters are shown in Table 5

<table>
<thead>
<tr>
<th>D(mm)</th>
<th>( V_\text{e}(\text{m/s}) )</th>
<th>( \varepsilon )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>39.9</td>
<td>1.072</td>
<td>1963×10^{-5}</td>
<td>599</td>
</tr>
</tbody>
</table>

TABLE V. CORRELATION PARAMETERS IN QUANTITATIVELY ANALYSIS

Two situations for four typical QTPO has been calculated. For situation 1, power angle is 20 degree. Current of transmission lines in different QTPO is shown in Table IV. Ambient air temperature is assumed as 20 °C. Temperature raising progress of different QTPO is shown in Fig. 5.

Fig. 5. Temperature progress of different QTPO in situation 1.

Assume that the safety temperature of transmission line is 100 °C. The system change into QTPO when time is zero. The four curves in Fig. 5 represents four typical QTPO. Before the temperature of transmission lines higher than threshold, the QTPO can be maintained. As shown in Fig. 5(a), QTPO which involves 4 lines can be kept about 650 minutes. QTPO which involves 3 lines can be kept about 900 minutes. The time is long enough operators to deal with faults. The area which is squared in Fig. 5(a) is zoomed in as shown in Fig. 5(b). For different types of QTPO which contains same number of lines, the longest operation time in QTPO is different. If one circuit is maintained in QTPO, the temperature raise faster.

For situation 2, power angle is 15 and ambient air temperature is 25 °C. Progress of time raising is shown in Fig. 6.

Fig. 6. Temperature progress of different QTPO in situation 1.

In this situation, the temperature of transmission lines will stabilize at about 75 °C as shown in Fig. 6(a). Temperature will not be a limitation in this situation. The area which is squared in Fig. 6(a) is zoomed in as shown in Fig. 6(b). Conclusion is same as that in situation 1. The more transmission lines are kept in QTPO, the faster temperature raising will be. For different QTPO which involves same transmission line, if one circuit is kept, the raising of temperature will be faster.

IV. CONCLUSION

The paper proposed a novel tripping and reclosing strategy. It can change the double circuits into QTPO after faults. The proposed scheme decrease the number of lines which need to
be tripped and reclosed. The number of fault types which all lines should be tripped is decreased obviously. More transmission power can be maintained and the possibility of reclosing to permanent fault can be decreased. It is benefit to the stability and reliability of system and gives a help to extend the work life of breakers. Using PSCAD/EMTDC, a typical double circuit lines on the same tower is built. According to simulation results, the feasibility and performance of QTPO is analyzed. Double circuits can operate in QTPO long enough for the operators to transfer load and deal with fault. Unbalance degree can meet the requirement of operation. Compared with conventional tripping and reclosing strategy, the novel strategy and QTPO have obvious advantages.

REFERENCES


