Online Evaluation Technology of Switching Overvoltage on No-Load Transmission Lines During Power Grid Restoration

Yizhao Wang
State Grid Shaanxi Electric Power Research Institute
Xi'an, China
wangyzngu@163.com

Zhihua Zhang
State Grid Shaanxi Electric Power Research Institute
Xi'an, China
zzhtsky123@163.com

Yanjie Hu
School of Electrical Engineering Xi'an Jiaotong University
Xi'an, China
huyanjie0423@163.com

***Abstract*—The research content of this paper is the overvoltage problem at the end of the no-load closing transmission lines and its online evaluation technology in the process of power system restoration. It aims to support the decision-making of dispatchers in the face of extremely small probability events, and to prepare the necessary technical conditions for the development of relevant supporting systems, so as to achieve the purpose of fast and effective black start in case of power grid failure, improve the resilience of power grid. According to the closing conditions of no-load transmission lines in the process of power grid restoration, the equivalent circuit models are constructed. By solving the corresponding circuit differential equation, the expression of voltage at the end of no-load transmission line is obtained, and the factors influencing the voltage are figured out. The algorithm to determine the most serious closing condition of no-load transmission line is given based on the analyzation above, and the reliability of the algorithm is verified by simulation.**

***Keywords*—power system restoration; online evaluation; no-load transmission line; overvoltage**

I. Introduction

The expansion of power system scale, widespread application of renewable energy integration system, load increase and industrial structure adjustment lead to constant increase of the complexity of the power system. Besides, the economic requirements for grid operation make it gradually close to the operating limit. Therefore, the power system is facing more and more local and global outage risk [1]. How to improve the resilience of power grid is highly valued by power grid enterprises and researchers. Restoring the power supply in the faulty area is the priority after a power outage in the power system. The restoration process needs to meet the requirements of safety, high speed, stability, flexibility, and minimization of negative effects [2]. In this process, utilizing no-load closing operation of transformers and lines is inevitable.

Although in China a lot of analysis has been conducted on grid restoration problems related to the formulation of grid restoration plans, the search for optimal restoration paths, and the safety assessment of restoration plans, etc., the overvoltage problem during no-load closing operation of circuit breakers and transformers in the power grid restoration after a blackout have rarely been studied so far [3,4]. In the actual restoration process of the power system, the dispatcher needs to quickly determine the feasibility of the restoration operation, based on the offline restoration plan and work experience [5,6].

However, due to different initial conditions of the fault, the restoration process of the grid is diverse, leading to limited guiding significance of the offline restoration plan in the process. Therefore, in-depth research on the generation mechanism of overvoltage during the closing operation of circuit breakers on no-load transmission lines in the process of grid restoration, and online assessment of overvoltage risks, have important guiding significance for the rapid and safe restoration of the grid and the improvement of the resilience of the grid.

II. Solution of the Voltage at the End of No-Load Closing Transmission Line

A. Equivalent Circuit of the System on the Back Side of the Bus Bar

Taking the bus bar where the transmission line to be studied is located as the observation point, the original system on the back side of the bus bar is converted to the equivalent circuit according to Thevenin Theorems, as shown in Fig. 1.

In Fig. 1， $E\angle\varphi$ refers to the open-circuit voltage, Z_{in} refers to the input impedance.

B. Model of the Circuit Breaker

In order to restrain the closing overvoltage of no-load transmission lines, shunt resistance is installed for circuit breaker, known as the closing resistance on circuit breaker.

In the closing process of the circuit breaker, the auxiliary switch K_f is closed first, and the closing resistance R_f is connected into the system. After a few milliseconds, the main switch K_z is then closed. A few tens of milliseconds later, the auxiliary switch is disconnected and the closing resistance is withdrawn from the system. Thus, one closing operation of the circuit breaker is completed.

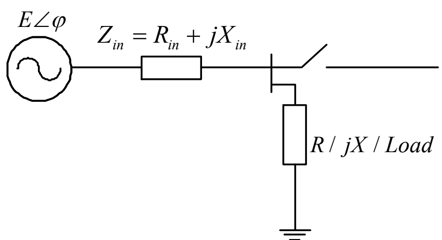


Fig. 1. Thevenin equivalent circuit of the system.

2020 IEEE Sustainable Power and Energy Conference (iSPEC) | 978-1-7281-9164-5/20/$31.00 ©2020 IEEE | DOI: 10.1109/ISPEC50848.2020.9351042

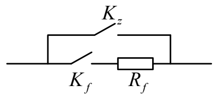


Fig. 2. The model of the circuit breaker.

The model of the circuit breaker is shown in Fig. 2.

TABLE I
EQUIVALENT CIRCUIT MODEL OF OVERHEAD TRANSMISSION LINES

Length range /km	Quantity
<100	horizontal-linear-type equivalent circuit
100~300	π-type or T-type equivalent circuit
>300	Distributed parameter circuit

C. Calculation of the Terminal Voltage on No-load Closing Transmission Line Model of the Circuit Breaker

In order to analyze the factors that affect the no-load closing overvoltage of transmission lines, it is necessary to build the equivalent circuit model of overhead transmission lines before the calculation. For overhead transmission lines with different length ranges, the equivalent circuit model to be selected is also different, as shown in Table I.

Among the three types of equivalent circuits, π- type or T- type equivalent circuit can be used to describe the transmission line within the range of 100km, while for the lines longer than 300km, the parameters of resistance, inductance and capacitance can be modified by employing corresponding correction coefficients on the basis of π-model or T- type equivalent circuit. Therefore, the transmission lines with the length range between 100~300km are selected for research, and the T-type equivalent circuit model as shown in Fig. 3 is built.

Before the circuit breaker of no-load line is closed, the residual voltage on the line is zero, and the initial voltage and current are zero, which brings:

$$u_c(0)=0\,,\ \left.\frac{du_c}{dt}\right|_{t=0}=0 \tag{1}$$

In order to quantitatively analyze the various factors affecting the closing voltage of no-load transmission lines, the differential equation for the circuit can be established as follow:

$$\begin{aligned}
E(t)&=(L_s+L_1\frac{s}{2})C_1 s\frac{d^2u_c(t)}{dt^2}+(R_f+R_1\frac{s}{2})C_1 s\frac{du_c(t)}{dt}+u_c(t)\\
&=LC\frac{d^2u_c(t)}{dt^2}+RC\frac{du_c(t)}{dt}+u_c(t)\\
E(t)&=E_m\sin(\omega t+\varphi)
\end{aligned} \tag{2}$$

Where $R=R_f+R_1\frac{s}{2}$; $L=L_s+L_1\frac{s}{2}$; $C=C_1 s$.

In (2), E_m refers to the amplitude of phase voltage on power supply side; ω refers to the angular frequency; φ refers to the initial phase angle of closing the transmission line; R_1、L_1、C_1 refer to resistance, inductance and capacitance to ground per unit length of transmission line.

This work was supported by Science and Technology Project Funding of State Grid Shaanxi Electric Power Company (No. B626KY190002).

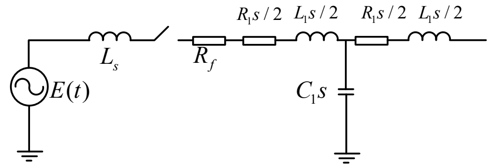


Fig. 3. T-type equivalent circuit model

Through observation, it can be observed that the circuit differential equation belongs to the second order non-homogeneous linear differential equation with constant coefficients. Equation (2) can therefore be transformed into the form as (3), the general solution and the special solution can then be solved respectively.

$$\frac{d^2u_c(t)}{dt^2}+\frac{R}{L}\frac{du_c(t)}{dt}+\frac{1}{LC}u_c(t)=\frac{1}{LC}E(t) \tag{3}$$

1) The General Solution:

For the second order nonhomogeneous linear differential equation with constant coefficients, the characteristic equation can be listed as follows:

$$r^2+\frac{R}{L}r+\frac{1}{LC}=0$$

The characteristic roots are obtained as follows:

$$r=-\frac{R}{2L}\pm\sqrt{\frac{R^2}{4L^2}-\frac{1}{LC}} \tag{4}$$

Considering the underdamped state of the system, which brings $R<2\sqrt{L/C}$, the characteristic roots of the equation can be written as:

$$r=\alpha\pm j\beta$$

Where $\alpha=-R/2L$, $\beta=\sqrt{1/LC-R^2/4L^2}$.

Then the general solution can be expressed as follows:

$$u_c(t)=e^{\alpha t}(C_1\cos\beta t+C_2\sin\beta t) \tag{5}$$

2) The Special Solution:

Because the second order non-homogeneous linear differential equation with constant coefficients has the following form on the right side:

$$\frac{1}{LC}E(t)=\frac{1}{LC}(E_m\sin\varphi\cdot\cos\omega t+E_m\cos\varphi\cdot\sin\omega t)$$

Therefore, the special solution can be expressed as follows:

$$u_c^*(t)=A_1\sin\omega t+A_2\cos\omega t$$

After substituting it into the original equation, the coefficient relationship is obtained as follows:

$$\begin{cases}(1-LC\omega^2)A_1-RC\omega A_2=E_m\cos\varphi\\ RC\omega A_1+(1-LC\omega^2)A_2=E_m\sin\varphi\end{cases}$$

The correlation coefficients are obtained as follows:

$$\begin{cases}A_1=E_m\dfrac{(1-LC\omega^2)\cos\varphi+RC\omega\sin\varphi}{(1-LC\omega^2)^2+(RC\omega)^2}\\[2ex] A_2=E_m\dfrac{(1-LC\omega^2)\sin\varphi-RC\omega\cos\varphi}{(1-LC\omega^2)^2+(RC\omega)^2}\end{cases} \tag{6}$$

Substituting the correlation coefficients into the special solution equation, the following results can be obtained:

$$\begin{aligned} u_c^*(t)&=E_m\frac{(1-LC\omega^2)\cos\varphi+RC\omega\sin\varphi}{(1-LC\omega^2)^2+(RC\omega)^2}\sin\omega t\\ &+E_m\frac{(1-LC\omega^2)\sin\varphi-RC\omega\cos\varphi}{(1-LC\omega^2)^2+(RC\omega)^2}\cos\omega t\\ &=E_m\frac{(1-LC\omega^2)\sin(\omega t+\varphi)}{(1-LC\omega^2)^2+(RC\omega)^2}-E_m\frac{RC\omega\cos(\omega t+\varphi)}{(1-LC\omega^2)^2+(RC\omega)^2}\\ &=E_m\sqrt{\frac{1}{(1-LC\omega^2)^2+(RC\omega)^2}}\sin(\omega t+\varphi+\varphi_1) \end{aligned} \tag{7}$$

Where $\tan\varphi_1=-\dfrac{RC\omega}{1-LC\omega^2}$.

3) The General Solution Coefficients:

Before the closing operation of no-load line, the residual voltage on the line is zero, and the initial voltage and current are both zero, by substituting the boundary conditions (1) into the calculation, the equation can be obtained as follows:

$$\begin{aligned} u_c(t)&=e^{\alpha t}(C_1\cos\beta t+C_2\sin\beta t)\\ &+E_m\sqrt{\frac{1}{(1-LC\omega^2)^2+(RC\omega)^2}}\sin(\omega t+\varphi+\varphi_1)\\ &=e^{\alpha t}(C_1\cos\beta t+C_2\sin\beta t)+E_m k_1\sin(\omega t+\varphi+\varphi_1) \end{aligned} \tag{8}$$

The correlation coefficient are obtained as:

$$\begin{cases} C_1=-E_m k_1\sin(\omega t+\varphi+\varphi_1)\\ C_2=E_m k_1\dfrac{\alpha\sin(\varphi+\varphi_1)-\omega\cos(\varphi+\varphi_1)}{\beta} \end{cases}$$

4) Expression of the closing voltage:

After the correlation coefficient of general solution is substituted into the formula, the expression of terminal voltage of no-load closing line can be obtained.

$$\begin{aligned} u_c(t)&=E_m k_1\sin(\omega t+\varphi+\varphi_1)-E_m k_1 e^{\alpha t}[\sin(\varphi+\varphi_1)\cos\beta t\\ &+\frac{\omega\cos(\varphi+\varphi_0)-\alpha\sin(\varphi+\varphi_0)}{\beta}\sin\beta t]\\ &=E_m k_1\sin(\omega t+\varphi+\varphi_1)-E_m k_1 e^{\alpha t}\frac{\sin(\varphi+\varphi_1)}{\sin(\varphi_2)}[-\sin(\varphi_2)\cos\beta t\\ &+\frac{\omega\cos(\varphi+\varphi_0)-\alpha\sin(\varphi+\varphi_0)}{\beta\sin(\varphi+\varphi_0)}\sin(\varphi_2)\sin\beta t]\\ &=E_m k_1\sin(\omega t+\varphi+\varphi_1)-E_m k_1 e^{\alpha t}\sin(\varphi+\varphi_1)\times\\ &\sqrt{1+[\frac{\alpha\sin(\varphi+\varphi_0)-\omega\cos(\varphi+\varphi_0)}{\beta\sin(\varphi+\varphi_0)}]^2}\sin(\beta t+\varphi_2)\\ &=E_m k_1[\sin(\omega t+\varphi+\varphi_1)-e^{\alpha t}k_2\sin(\varphi+\varphi_1)\sin(\beta t+\varphi_2)] \end{aligned} \tag{9}$$

Where

$$\begin{aligned} k_1&=\sqrt{\frac{1}{(1-LC\omega^2)^2+(RC\omega)^2}}\\ k_2&=\sqrt{1+[\frac{\alpha\sin(\varphi+\varphi_0)-\omega\cos(\varphi+\varphi_0)}{\beta\sin(\varphi+\varphi_0)}]^2}\\ \tan\varphi_2&=\frac{-\beta\sin(\varphi+\varphi_1)}{\alpha\sin(\varphi+\varphi_1)-\omega\cos(\varphi+\varphi_1)} \end{aligned}$$

III. Influential Factors of Voltage at the End of No-Load Closing Transmission Line

By analyzing the expression of the terminal voltage, the terminal voltage of no-load closing transmission line is formed by superposition of power frequency component and free oscillation component. At the moment of closing the circuit breaker, the power supply potential E(t) charges the energy storage elements in the line and generates the attenuated free component voltage, and the power frequency component voltage is generated by the continuous power supply. The superposition of the two causes the over-voltage phenomenon at the end of the no-load transmission line.

TABLE II
THE RELEVANT PARAMETERS SET IN THE STUDY

Line parameters	Unit	Value
E	(kV)	330
R_1	(Ω/km)	0.01847
L_1	(H/km)	8.78853×10^{-4}
C_1	(F/km)	1.329×10^{-8}
s	(km)	145.414

In the expression, the factors affecting the voltage at the end of the no-load closing line include: closing phase φ, closing resistance R_f, input impedance of bus back side system Z_s, line length s, line parameters R_1、L_1、C_1 (resistance, inductance and capacitance to ground of the transmission line per unit length).

For different lines under the same voltage level, s、R_1、L_1、C_1 have little difference, so these three line parameters have little influence on the voltage at the end of the

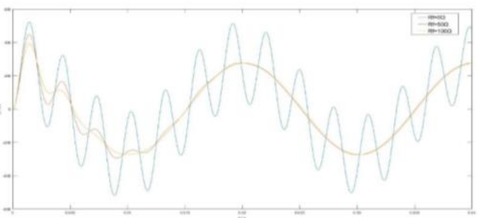
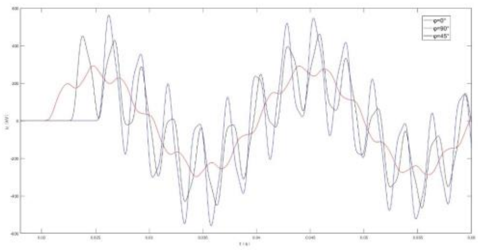
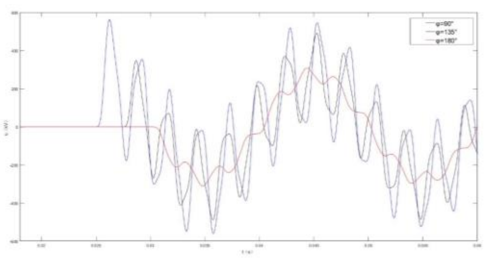


Fig. 4. Figure of voltage at the end of no-load closing transmission line varing with closing resistance



(a)



(b)

Fig. 5. Terminal voltage waveform of no-load closing line varying with the closing phase angle when $R_f = 0\ \Omega$

no-load closing line. What's more, for the line under study, the input impedance of the bus back side system is determined. Therefore this paper focuses on the influence of closing phase φ and closing resistance R_f on the voltage.

The relevant parameters are set as shown in Table II.

A. Influence of Closing Resistance

Fig. 4 shows how the voltage at the end of no-load closing line varies with the closing resistance.

In Fig. 4, green, yellow and red lines correspond to the voltage waveforms when closing resistance is set as 0 Ω, 50 Ω and 100 Ω, respectively.

It can be seen that when there is a closing resistance, the overvoltage oscillation at the end of no-load line is reduced, and the peak value of overvoltage decreases obviously, and decreases with the increase of closing resistance value.

B. Influence of Closing Phase Angle with No Closing Resistance Installed

Taking the closing resistance R_f = 0 Ω, the figure of the terminal voltage waveform of no-load closing line varying with the closing phase is shown in Fig. 5.

In Fig. 5 (a), red, black and blue lines are terminal voltage waveforms when closing phase angle φ is set as 0°, 45°, 90°. In Fig. 5 (b), blue, black and red lines are terminal voltage waveforms when φ is set as 90°, 135°, 180°, respectively.

It can be seen from Fig. 5 that the most serious over-voltage situation will be generated when circuit breaker on the no-load transmission line closes at some certain moment near when the power supply reaches the peak value.

Setting R_f=0Ω，φ=90° to get the voltage waveform at the end of no-load closing line, as shown in Fig. 6.

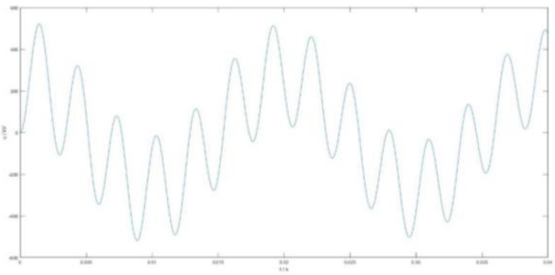


Fig. 6. Waveform of voltage at the end of no-load closing transmission line when R_f=0Ω，φ=90°.

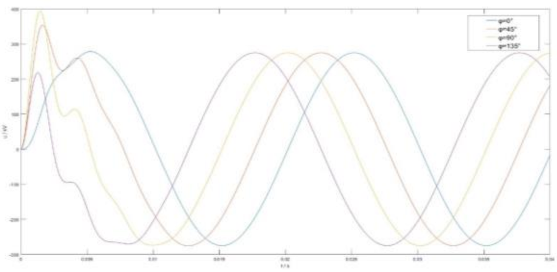


Fig. 7. Voltage at the end of no-load closing line varying with closing phase angle when R_f=100Ω.

It can be seen from Fig. 6 that when the closing resistance is not used to reduce the overvoltage oscillation, the overvoltage amplitude at the end of the line can reach about twice of the rated voltage when switching on near the peak value of the power supply voltage.

C. Influence of Closing Phase with Closing Resistance Installed

In order to reduce the impact of overvoltage oscillation, appropriate closing resistance should be set in real system. Taking closing resistance R_f =100Ω to get how the voltage waveform at the end of no-load closing line varying with closing phase, as shown in Fig. 7.

In Fig. 7, the blue, red, yellow and purple lines correspond to conditions that closing phase is set as 0°, 45°, 90° and 135°, respectively.

It can be seen from Fig. 7 that when switching on near the peak value of power supply voltage, the overvoltage is the most serious. After excluding the influence of voltage oscillation, the conclusion is the same as that obtained from Fig. 6.

IV. DETERMINATION OF THE MOST SERIOUS CONDITION OF NO-LOAD TRANSMISSION LINE CLOSING

For a certain power system, the closing resistance R_f, input impedance at the back side of the system Z_s, line length s and line parameters R_1、L_1、C_1 are all determined. Therefore, to determine the most serious closing condition is to determine which closing phase angle could lead to the most serious overvoltage at the end of no-load line.

A. Determination of Inspection Time Length

Fig. 8 shows how terminal voltage of no-load closing line varies with closing phase angle and time.

The following conclusions can be drawn from fig. 8:

- The voltage at the end of no-load closing line consists of two parts: the power frequency component caused by power supply voltage and the free oscillation component;
- The free oscillation component, generated at the moment of no-load line closing, will be attenuated in a few milliseconds, but it will lead to the generation of peak overvoltage at the end of the line.

For the power frequency component voltage, only 0~T/2 needs to be investigated; for the free oscillation component voltage, the attenuation will be completed

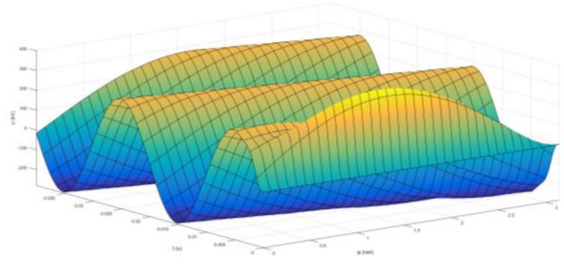


Fig. 8. Waveform of voltage at the end of no-load closing line varying with closing phase angle and time.

within 0~T/2. Therefore, only the line terminal voltage within half a cycle is considered in calculation and simulation verification.

B. Calculation of Impedance at the Back Side of Bus Bar Based on Fault Component Feature Method

When a fault occurs on the line, according to the superposition principle, its state can be regarded as the superposition of no-fault state and additional fault state.

$$\dot{U}_M = \dot{U}_{Mf} + \Delta\dot{U}_M$$
$$\dot{I}_M = \dot{I}_{Mf} + \Delta\dot{I}_M$$

For fault component extraction, there are mainly differential filtering method and feature method.

Differential filtering method is the main application method at present, but the fault component obtained is actually the power frequency variation or sudden variable, which can only reflect the fault component within a short period of the first one or two cycles of the fault, and the value obtained beyond this time could not reflect the fault component.

In the first tens of milliseconds of fault occurrence, the fault component current contains a large number of transient components, which makes the calculation error of impedance larger. If a long time and stable fault component is used to calculate the impedance, the result can be obtained more accurately.

In order to obtain the long-time fault component after the fault, the characteristic method is used.

In the case of asymmetric short circuit fault, negative sequence component and zero sequence component exist for a long time. After obtaining the negative sequence and zero sequence components, the fault type and special phase are determined according to the results of phase selection, and different boundary conditions can be obtained:

1) *single-phase grounding fault:*

$$\Delta\dot{I}_{m1} = \dot{I}_{m2} = \dot{I}_{m0}$$

2) *two-phase short circuit fault:*

$$\Delta\dot{I}_{m1} = -\dot{I}_{m2}$$
$$\dot{I}_{m0} = 0$$

3) *two-phase grounding fault*

$$\Delta\dot{I}_{m1} = -(\dot{I}_{m2} + \frac{c_{m1}}{c_{m2}}\dot{I}_{m0})$$

According to the boundary conditions above, the positive sequence fault component can be derived, and then the fault component of each phase can be calculated according to the following formula:

$$\begin{bmatrix}\Delta\dot{I}_{mA}\\ \Delta\dot{I}_{mB}\\ \Delta\dot{I}_{mC}\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ a^2 & a & 1\\ a & a^2 & 1\end{bmatrix}\begin{bmatrix}\Delta\dot{I}_{m1}\\ \dot{I}_{m2}\\ \dot{I}_{m0}\end{bmatrix}$$

$$a = e^{j120^\circ}$$

The fault characteristics of phase A to phase B short circuit fault are considered here. Three formulas are derived to solve the bus back impedance as follows:

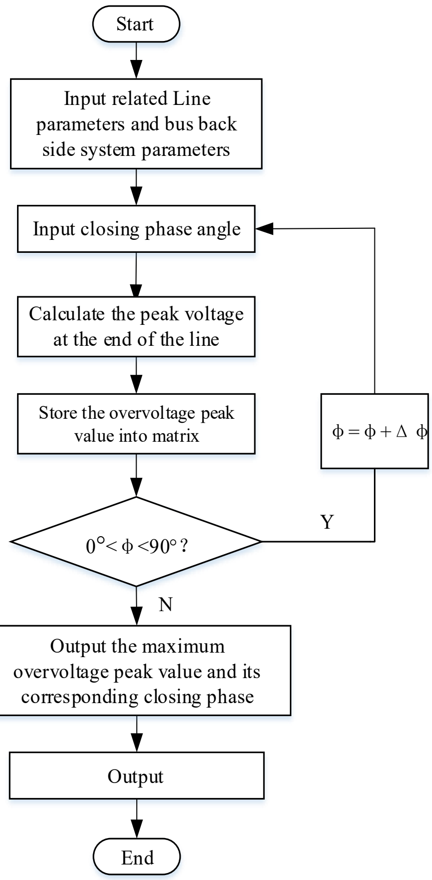


Fig. 9. Flow chart of solving the most serious condition.

$$Z_s = -\frac{\Delta\dot{U}_{m1}}{\Delta\dot{I}_{m1}}$$
$$Z_s = -\frac{\dot{U}_{m2}}{\dot{I}_{m2}} \qquad (10)$$
$$Z_s = -\frac{\Delta\dot{U}_{mA} - \Delta\dot{U}_{mB} + j\sqrt{3}\Delta\dot{U}_{mC}}{\Delta\dot{I}_{mA} - \Delta\dot{I}_{mB} + j\sqrt{3}\Delta\dot{I}_{mC}}$$

C. Determination of the Most Serious Condition of No-load Transmission line closing

According to the voltage expression at the end of no-load closing line, the algorithm for solving the closing phase angle that would cause the most serious voltage and

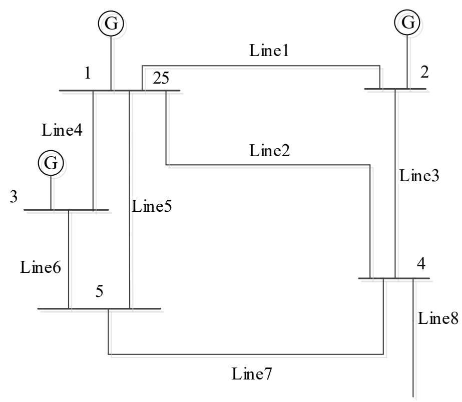


Fig. 10. 330kV five node transmission network model.

the corresponding overvoltage peak value can be listed. The flow chart is shown in Fig. 9.

D. Case Study

The 330kV five node transmission network model is built as shown in Fig. 10.

In Fig. 10, Line 8 is the line to be closed with no load at the end. Set the line parameters as shown in Table III, and set the line length as shown in Table IV.

Based on (10), the impedance on the back side of the bus bar is calculated as Zs=1.1748+j15.5379Ω. The comparison between the calculation results and the simulation results is shown in Table V.

This paper aims to evaluate the overvoltage to avoid accidents, so only when the calculated value is higher than the simulation value, the evaluation result is meaningful. It can be seen from Table V that the calculated voltage value is generally larger than the simulation result. When the length of the no-load closing line is continuously increased, the calculated voltage value is getting more close to the simulation result. When the length of the no-load closing line is increased to 300km, the error is only -0.1094kv.

If shorten the length of each line in the bus back side system, as shown in table VI. Based on (10), the impedance on the back side of the bus bar is calculated as Zs=0.8004+j10.7188Ω. After updating the line length, the comparison between the formula calculation results and the simulation results is shown in Table VII.

TABLE III
THE PARAMETERS OF THE TRANSMISSION LINES IN THE CASE

Line	Positive sequence parameter			Zero sequence parameter		
	R1 e-5 Ω/m	XL1 e-4 Ω/m	XC1 MΩ*m	R0 e-4 Ω/m	XL0 e-3 Ω/m	XC0 MΩ*m
1，5	2	2.81	254.6479	2	0.65	365.4534
2，6	1.9	2.72	263.9385	1.68	0.77	377.1444
3，7	1.88	2.67	242.6142	1.64	0.80	367.5634
4，8	1.70	2.10	171.1343	1.68	1.35	422.1617

TABLE IV
THE LENGTHS OF THE TRANSMISSION LINES IN THE CASE

Line	1	2	3	4	5	6	7
Length (km)	155	145	160	95	170	130	215

TABLE V
THE CALCULATION AND SIMULATION RESULTS

Line 8 (km)	Simulation Result		Calculation Result		ΔUc (kV)
	φ (°)	Uc (kV)	φ (°)	Uc (kV)	
150	60.84	384.6409	75.42	402.6974	18.0565
180	60.48	384.4392	73.08	398.0015	13.5623
210	60.84	384.1332	70.74	394.0486	9.9154
240	60.84	383.9179	68.40	390.5827	6.6648
270	62.28	384.9376	66.24	387.4541	2.5165
300	60.84	384.6606	63.90	384.5512	-0.1094

Where ΔUc=Uc(calculation result)-Uc(simulation result).

TABLE VI
THE NEW LENGTHS OF THE TRANSMISSION LINES IN THE CASE

Line	1	2	3	4	5	6	7
Length (km)	120	100	100	80	135	90	190

TABLE VII
THE NEW CALCULATION AND SIMULATION RESULTS

Line8 (km)	Simulation Result		Calculation Result		ΔUc (kV)
	φ(°)	Uc(kV)	φ(°)	Uc(kV)	
150	70.92	382.7318	78.66	401.0070	18.2752
180	70.92	382.9718	76.32	395.9273	12.9555
210	70.92	383.3493	73.98	391.8602	8.5109
240	70.92	384.6509	71.82	388.8876	4.2367
270	70.92	383.9876	69.48	385.9797	1.9921
300	71.28	383.3220	67.14	383.3190	-0.003

Where ΔUc=Uc(calculation result)-Uc(simulation result).

It can be seen from Table VII that the calculated voltage value is generally greater than the simulation result. Even if the no-load closing line is extended to 300km, the error is only -1.9103kv.

Therefore, the calculation method to determine the most serious line no-load closing condition is reliable and effective.

V. CONCLUSION

The results and conclusions of this paper can be summarized as follows

- By constructing the equivalent circuit models, the corresponding circuit differential equation is solved, and the expression of the voltage at the end of the no-load closing line is obtained. Based on the analyzation of the expression, the influential factors of the voltage are obtained, including closing phase φ , closing resistance Rf, input impedance of bus back side system Z_s, line length s, line parameters R_1, L_1, C_1 (resistance, inductance and capacitance to ground of the transmission line per unit length).
- An algorithm to determine the most serious closing condition of no-load transmission line is proposed, and the reliability of the algorithm is verified by the simulation of a five-node 330kV transmission system model.

REFERENCES

[1] Teng Yufei, Ding Lijie, Tang fan, et al. Risk identification of harmonic voltage distortion caused by inrush current based on harmonic mutual impedance [J]. Power automation equipment, 2014, 34 (8): 155-161.
[2] Du Yin. Study on voltage stability of weak link system [D]. Zhejiang University, 2006.
[3] Zhang Baohui, Yin Xianggen. Power system relay protection (2nd Edition) [M]. Beijing: China Electric Power Press, 2005:15.
[4] Wang Xifan. Analysis of modern power system [M]. Beijing: Science Press, 2003:13-17.
[5] Gong Qi. Generation mechanism and suppression measures of no load line closing overvoltage [J]. Science and technology innovation guide, 2019,16 (21): 59-60.

[6] Shao Yu, Bai Shuyu, Dong Rui. Research on closing overvoltage of no load line based on EMTP [J]. Henan science and technology, 2018 (25): 139-141.

[7] I Sadeghkhani, A Ketabi, R Feuillet. Artificial-intelligence-based techniques to evaluated switching overvoltages during power system restoration[J]. Advances in Artificial Intelligence, 2013,2013(2):1-8.

[8] Liang Mengke, Teng Huan, Li Xuesong, Wu zeqiong. Influence of optimal closing phase on no-load line closing overvoltage [J]. Science and technology and engineering, 2017,17 (31): 245-251.

[9] Mo Wenhuo. Analysis and Research on switching overvoltage based on no-load line closing [J]. Enterprise technology and development, 2015 (z1): 60-62.

[10] Yang Jitong, Zhao Yi, Yang Bin, Dai Qing. Analysis of no-load switching overvoltage during power grid black start recovery [J]. Journal of Shenyang Institute of Engineering (NATURAL SCIENCE EDITION), 2015,11 (03): 255-259.

[11] Zhang Lei, e Shiping. Simulation study on closing resistance of transmission line breaker [J]. Northeast electric power technology, 2014,35 (12): 29-30.