Voltage Characteristic Analysis of Ultra-high Voltage Half-wavelength Transmission System Based on Wave Process Method

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Abstract—The voltage characteristics of a half-wavelength transmission (HWLT) system lack mechanism explanation and systematic summary. In this paper, both the steady-state and fault voltage characteristics are analyzed and explained based on the wave process method. An analysis model is established for HWLT lines and wave propagation equations with different terminal conditions are deduced. For steady-state conditions, voltage profiles along HWLT lines are depicted and partial overvoltage occurs when there is an overload or low-power factor. In addition, fault voltage characteristics are analyzed under load-rejection or short-circuit conditions. The series resonance overvoltage will happen when short-circuit faults occur at certain positions and its peak value is influenced by grid strength or fault type. Furthermore, a refined transmission line model is presented to consider non-ideal factors and simulation results demonstrate that geomorphic conditions and electromagnetic environments influence line voltage characteristics to a certain extent.

Index Terms—Half-wavelength transmission, wave process method, steady-state voltage, fault voltage, non-ideal factor

I. INTRODUCTION

The demand for fast-growing electric power has raised the necessity of transmitting power through very long distances from power plants to load centers [1]. This problem can be addressed by the use of high-voltage direct current (HVDC) technology and high-voltage alternating current (HVAC) technology [2]-[4]. However, regarding an AC alternative, the regular solution is the use of shunt and series compensated lines not longer than 400 km, which are unable to satisfy the demand of long-distance power transmission [5]. Another alternative has been studied which is called half-wavelength transmission (HWLT) system. The length of an ideal and unturned HWLT line is about 3000 km at 50 Hz or 2500 km at 60 Hz. It has shown advantages in technical and economical aspects, primarily for not requiring reactive compensation or intermediate substations between the terminals [6].

HWLT technology was first proposed by former Soviet scholars in the 1940’s [7]. Experts from the United States, India, Italy and other countries also conducted researches on natural or tuned HWLT in the following decades [8]-[11]. However, in the 20th century, low-power consumption demand and technology bottle-necks discouraged the further development of HWLT technology. But recently, the rapid load increases in the use of fossil fuels have caused more and more serious environmental pollution problems. HWLT began to be treated as a feasible alternative and attracted considerable interest. More theoretical analysis, simulation and engineering tests of HWLT technology have begun [12]-[18]. Moreover, the feasibility studies have been carried out in Brazil [5], [19]. According to these study results, this transmission technology has some particular characteristics and behaviors, which affects the design, operation and protection of the power system. Specifically, results in [8] showed that a load greater than the surge impedance loading (SIL) causes the peak value of voltage to rise in the middle of the line and conversely, load decreases cause voltage dip. In [9], it was found that power-frequency overvoltage during short-circuit condition is inevitable along the HWLT line, and magnitude reaches maximum when the fault occurs at certain points near the terminals. In [6], based on electromagnetic transient simulation, fault characteristics of a wide variety of load conditions, power factors and fault scenarios were analyzed.

Nevertheless, most of the existing research conclusions about voltage characteristics of HWLT systems are based on the simulation results, and there is a lack of in-depth analysis and mechanism explanations. For steady-state operation conditions, it is found that the voltage profiles along the HWLT line fluctuate remarkably with different transmitted power, but little analysis of the quantitative relationship has been done. For fault conditions, the serious fault mechanism and its influence factors need further research. In addition, most of the studies above are carried out for an ideal lossless hypothesis. In order to obtain more accurate analysis conclusions, line loss and other non-ideal factors need to be considered. Aiming to overcome these shortcomings, two
contributions are presented in this paper. Firstly, the steady-state voltage and fault voltage characteristics are explained comprehensively and systematically by the wave process method. The change of the impedance at the receiving end has a significant influence on the voltage and current profiles along the transmission line, which clarifies the causes for particular characteristics. Secondly, by considering variant geomorphic conditions and the electromagnetic environment of the transmission corridor, a refined transmission line model is presented.

II. MATHEMATICAL MODELING OF LONG LOSSLESS TRANSMISSION LINES

A. Distributed Parameter Model of Long Transmission Lines

Based on a distributed parameter model, the voltage and current relationship along long transmission lines can be represented by the hyperbolic function of the sinusoidal steady-state solution [8].

\[
\begin{align*}
U_x &= U_z \cosh(\gamma x) + j \gamma Z_z \sinh(\gamma x) \\
I_x &= I_z \cos(\gamma x) + j Z_z \sin(\gamma x)
\end{align*}
\]

where \( \gamma = \alpha + j \beta = \sqrt{z_0} y_0 \) is the line propagation coefficient, \( z_0 = r_0 + j x_0 \) and \( y_0 = g_0 + j b_0 \) are the impedance and admittance per unit length, respectively; \( Z_z = \sqrt{z_0} y_0 \) is the line characteristic impedance; \( U_z \) and \( I_z \) are the receiving-end voltage and current, respectively; and \( U_x \) and \( I_x \) are the voltage and current at point \( x \), respectively.

For a hypothetical lossless line, \( r_0 = 0, g_0 = 0 \), (1) can be rewritten as:

\[
\begin{align*}
\dot{U}_x &= U_z \cos(\beta x) + j \beta Z_z \sin(\beta x) \\
\dot{I}_x &= I_z \cos(\beta x) + j \frac{U_z}{Z_z} \sin(\beta x)
\end{align*}
\]

B. Reactive Power Distribution of Long Transmission Lines

The charging reactive power generated in the \( l \)-length line is represented by the integration of the susceptance per unit length:

\[ Q_{Cs} = \int_0^l \dot{U}_x^* b_z Z_z \, dx \]  

The reactive power loss consumed in the \( l \)-length line is represented by integration of the reactance per unit length:

\[ Q_{ls} = \int_0^l I_x^* \frac{x_0}{Z_z} x_0 \, dx \]

If the terminal impedance is equal to \( Z_z \), the power in the load is named the SIL:

\[ L_{SIL} = \frac{|U_z|^2}{Z_z} \]  

Equation (2) can be written in the form of terminal power regarding receiving-end voltage \( U_z = U_z \angle 0^\circ \) as voltage reference and SIL as the capacity reference. Then, the voltage \( U_x \) and current \( I_x \) relationship along transmission lines in form of per-unit value are shown as follow.

\[
\begin{align*}
\dot{U}_r &= \cos(\beta x) + Q_z \sin(\beta x) - j P_z \sin(\beta x) \\
\dot{I}_r &= P_z \cos(\beta x) + j (\sin(\beta x) - Q_z \cos(\beta x))
\end{align*}
\]

where \( P_z \) and \( Q_z \) represent the per-unit values of active power and reactive power, respectively.

Based on (5), the charging reactive power of a long transmission line is:

\[ Q_{C*} = \frac{b_z Z_z}{2 \beta} \left[ (P_z^2 + Q_z^2)(\beta l - \cos(\beta l) \sin(\beta l)) + 2Q_z \sin^2(\beta l) \right] + \sin(\beta l) \sin(\beta l) + \beta l \]  

Similarly, the reactive power loss of a long transmission line is:

\[ Q_{L*} = \frac{x_0}{2Z_z \beta} \left[ (P_z^2 + Q_z^2)(\beta l + \cos(\beta l) \sin(\beta l)) - 2Q_z \sin^2(\beta l) \right] - \cos(\beta l) \sin(\beta l) + \beta l \]  

The surplus reactive power is the difference between the charging reactive power and reactive power loss which significantly influences the voltage profiles along the transmission line. According to (7) and (8), it can be noted that the charging power and reactive power loss have a relationship with the line length and transmitted power. Figure 1 shows that the surplus reactive power appears as a periodical variation when the length of the line increases. When the length of a transmission line is shorter than \( \lambda/4 \) and active power is lower than the SIL, surplus reactive power will present a capacitive effect which rouses an increase in voltage at the receiving end. This phenomenon is named the Ferranti effect which is visible for traditional ultra-high voltage (UHV) lines. When the line length is half-wavelength or its multiple, the charging reactive power and reactive power loss becomes equal, which means the transmission line itself neither generates nor absorbs reactive power. Therefore, no additional reactive power compensation is needed to balance surplus reactive power between the sending end and receiving end. HWLT technology economically utilizes this advantage for long-distance power transmission.
C. Wave Process of Long Transmission Lines

In the distribution parameter circuit, voltages and currents are the results of the function of both time and distance. The dynamic equations are in a form of partial differential. In the following, the wave propagation process will be analyzed in different receiving-end impedance conditions.

Rewrite (2) as the form of a natural logarithm:

\[
\begin{align*}
\dot{U}_s &= \frac{1}{2} (\dot{U}_2 + Z_c \dot{I}_2) e^{j\beta x} + \frac{1}{2} (\dot{U}_2 - Z_c \dot{I}_2) e^{-j\beta x} \\
\dot{I}_s &= \frac{1}{2} (\dot{I}_2 + \frac{\dot{U}_2}{Z_c}) e^{j\beta x} + \frac{1}{2} (\dot{I}_2 - \frac{\dot{U}_2}{Z_c}) e^{-j\beta x}
\end{align*}
\]

(9)

Voltage wave and current wave can be expressed as a superposition of incident wave and reflected wave. The ratio of the magnitudes of the reflected and incident voltage (current) waves is termed the reflection coefficient \(N\):

\[
N = \frac{Z_2 - Z_c}{Z_2 + Z_c} e^{-j\phi}
\]

(10)

where \(Z_2\) is load impedance of line terminal.

The voltage magnitudes along the transmission line are expressed as a function of the reflection coefficient:

\[
U_x = U_s^* \sqrt{1 + N^2 + 2N\cos(2\beta x)}
\]

(11)

where \(U_s^*\) is the magnitude of the reflected voltage wave.

By analyzing the incident wave and reflected wave traveling along the transmission line, the voltage and current profiles for different terminal conditions are explained. Specially, in some fault conditions, standing waves arouse energy transitions between electric and magnetic fields which influence the normal power propagation.

III. STEADY-STATE ANALYSIS OF HWLT LINES

This section focuses on the steady-state voltage characteristics of an ideal HWLT line in normal operation conditions. When active power and power factors change, voltage profiles fluctuate remarkably which may result in overvoltage. The maximum voltage value and its position are deduced.

A. Steady-state Voltage Profiles Along HWLT Line

When the receiving-end impedance matches with the characteristic impedance \(Z_2 = Z_c\), (8) is simplified as:

\[
\begin{align*}
\dot{U}_s &= \dot{U}_2 e^{j\beta x} \\
\dot{I}_s &= \dot{I}_2 e^{j\beta x}
\end{align*}
\]

(12)

In SIL, the voltage and current waves travel in one direction with no reflections in the other direction. The \(\dot{U}_s\) and \(\dot{I}_s\) along the transmission line are in phase without attenuation.

Voltage profiles for different active power (\(Q_{\infty} = 0\)) are shown in Fig. 2. When \(P_{\infty} > L_{\text{sil}}\), that means \(Z_2 < Z_c\). According to (10), we can acquire \(N < 0\). It can be obtained from (11) that the voltages along the transmission line reach a minimum at \(x = 0, \lambda/2, \ldots\) and the voltages along the transmission line reach a maximum at \(x = \lambda/4, 3\lambda/4, \ldots\). Similar to the above analysis, when \(P_{\infty} < L_{\text{sil}}\), as \(Z_2 > Z_c\), the voltages along the transmission line reach a minimum at \(x = \lambda/4, 3\lambda/4, \ldots\), and the voltages along the transmission line reach a maximum at \(x = 0, \lambda/2, \ldots\).

From another perspective, voltage profiles for different power factors (\(P_{\infty} = 1, Q_{\infty} > 0\)) are shown in Fig. 3. The voltages along the line appear to be a sinusoidal trend, and the lower the power factor, the higher the voltage value along the line.

Fig. 2. Voltage profiles along the half-wavelength line for different active power (\(Q_{\infty} = 0\)).

B. Maximum Voltage and Its Position

In order to acquire maximum voltage and its position, the magnitude of voltage along the HWLT line can be obtained based on (6):

\[
U_x = \sqrt{\cos(\beta x) + (Q_{\infty}\sin(\beta x))^2 + (P_{\infty}\sin(\beta x))^2}
\]

(13)

By seeking the extreme value point of function \(U_x = f(x)\), the position of the maximum voltage \(x_{\text{max}}\) can be represented as (14). The magnitude value \(U_{\text{max}}\) is obtained by substituting the value of (14) into (13).
\[ x_{\text{max}} = \frac{1}{\beta} \arctan \left( \frac{1}{2Q_{2^*}} \right) \left( P_{2^*}^2 + Q_{2^*}^2 \right) \left( 1 \pm \sqrt{1 + 2Q_{2^*} - 2P_{2^*} + (P_{2^*}^2 + Q_{2^*}^2)^2} \right) \]  

(14)

IV. FAULT VOLTAGE ANALYSIS OF HWLT LINES

When load-rejection or short-circuit faults occur, the HWLT line has some particular characteristics and behaviors compared with normal operation conditions. In this section, the voltage mechanism analysis for load-rejection and short-circuit faults are presented in detail. Then, the characteristic regularities for different types of faults and fault positions are summarized.

A. Fault Equivalent Circuit of HWLT Systems

Without loss of generality, the fault equivalent circuit of the HWLT system is established in Fig. 4. Point \( f \) is the fault point; \( l \) is the distance from the fault point to the sending end; \( Z_{\text{eq}1}, Y_{\text{eq}1}, Z_{\text{eq}2}, Y_{\text{eq}2} \) are the equivalent impedance and admittance parameters of the \( \pi \)-type circuit, respectively; \( I_{f1} \) and \( I_{f2} \) are the steady-state short-circuit currents from the sending-end and receiving-end systems, respectively; \( Z_s \) is the additional impedance at the fault point; and \( E_1 \) and \( E_2 \) are the equivalent electrical potentials of the sending-end and receiving-end systems, respectively.

![Fig. 4. Fault equivalent circuit of UHV HWLT system.](image)

B. Load-rejection Condition

If load-rejection happens, the receiving-end impedance \( Z_s \rightarrow \infty \), and the current \( I_s = 0 \), (2) is simplified as:

\[
\begin{align*}
\dot{U}_s &= jZ_s \dot{I}_s \sin(\beta x) \\
\dot{I}_s &= jZ_c \dot{U}_s \sin(\beta x)
\end{align*}
\]

(15)

The input impedance (in the direction of the receiving-end) at point \( x \) along the transmission line is:

\[ Z_i(x) = -jZ_s \cot(\beta x) \]

(16)

As shown in Fig. 5(a), input impedance is capacitive in the range of \( 0 < x < \frac{\lambda}{4}, \frac{\lambda}{2} < x < \frac{3\lambda}{4}, \ldots \) and appears inductive in the range of \( \frac{\lambda}{4} < x < \frac{\lambda}{2}, \frac{3\lambda}{4} < x < \lambda, \ldots \). At \( x = 0, \frac{\lambda}{2}, \lambda, \ldots \), \( Z_i \rightarrow \infty \), parallel resonance occurs; or at \( x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \ldots \), \( Z_i \rightarrow 0 \), series resonance occurs.

Therefore, when load-rejection occurs at the receiving-end, the terminal currents are \( |\dot{I}_s| = |\dot{I}_f| = 0 \) and the terminal voltages are \( |\dot{U}_s| = |\dot{U}_f| = |\dot{U}_i| \). The voltage magnitudes of the two terminals are equal. There is no obvious overvoltage at the terminal caused by the Ferranti effect. The voltage magnitude depends on equivalent electrical potential \( E_1 \), equivalent impedance \( Z_s \) and transmitted power before load-rejection fault.

![Fig. 5. Input impedance \( Z_i \) varying with length of transmission line \( \lambda \). (a) Terminal open circuit. (b) Terminal short circuit.](image)

C. Three-phase-to-ground Fault

In Fig. 4, when three-phase-to-ground fault occurs at point \( x \), the complete HWLT line is divided into two separate parts. The voltage at fault point \( U_f = 0 \), and additional impedance \( Z_s = 0 \). For sending-end side, based on (2), the voltage and current along HWLT line are simplified as:

\[
\begin{align*}
\dot{U}_s &= jZ_e \dot{I}_s \sin(\beta x) \\
\dot{I}_s &= jZ_c \dot{U}_s \sin(\beta x)
\end{align*}
\]

(17)

The input impedance (in the direction of fault point) at \( x \) point along transmission line is:

\[ Z_i(x) = \frac{\dot{U}_s}{\dot{I}_s} = jZ_e \tan(\beta x) \]

(18)

As shown in Fig. 5(b), input impedance is capacitive in the range of \( \frac{\lambda}{4} < x < \frac{\lambda}{2}, \frac{3\lambda}{4} < x < \lambda, \ldots \) and appears inductive in the range of \( 0 < x < \frac{\lambda}{4}, \frac{\lambda}{2} < x < \frac{3\lambda}{4}, \ldots \). At \( x = 0, \frac{\lambda}{2}, \lambda, \ldots \), \( Z_i = 0 \), series resonance occurs; or at \( x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \ldots \), \( Z_i \rightarrow \infty \), parallel resonance occurs.

The steady-state short-circuit current supplied by sending-end electrical potential is:

\[ \dot{I}_s(x) = \frac{\dot{E}_1}{Z_i + Z_i(x)} \]

(19)

The fault position has a great influence on the magnitude of overvoltage and overcurrent. The equivalent impedance of system is usually inductive, but the input impedance of transmission line appears to be capacitive in the range of \( \frac{\lambda}{4} < x < \frac{\lambda}{2} \). In particular, when the total impedance \( Z_i + Z_i(x) = 0 \), the denominator of (19) will tend to be zero. Series resonance happens and creates a surge in short-circuit current. The series resonance point tends to reach \( \frac{\lambda}{2} \) with decrease of impedance of sending-end system. The position that causes a series resonance is called the severe fault point. Hence, there are two severe fault points near terminals caused by sending-end and receiving-end systems, respectively. Substituting the short-circuit current value into (17), the maximum magnitude of voltage can be obtained. The posi-
tion is at \( i/4 \) away from fault point where \( \beta l = 90^\circ \).

\[
U_{\text{max}} = j\beta Z_r
\]  

(20)

### D. Single-phase-to-ground Fault

The symmetric component method is adopted to solve the asymmetrical faults problem [20]. As for the single-phase-to-ground fault in phase A, the relationships among the sequence components are:

\[
\begin{align*}
I_{ka1} & = I_{ka2} = I_{ka0} = \frac{U_{00}}{Z_{11} + Z_{22} + Z_{00}} = \frac{1}{3} I_{ka} \\
U_{ka1} + U_{ka2} + U_{ka0} & = U_{00} \\
Z_{11} & = Z_{11}' \parallel Z_{11}'' \\
Z_{22} & = Z_{22}' \parallel Z_{22}'' \\
Z_{00} & = Z_{00}' \parallel Z_{00}''
\end{align*}
\]  

(21)

(22)

where \( I_{ka1}, I_{ka2}, I_{ka0} \) are positive, negative and zero sequence short-circuit currents, respectively; \( I_{ka} \) is the short-circuit current of phase A; \( U_{ka1}, U_{ka2}, U_{ka0} \) are the positive, negative and zero sequence voltages, respectively; \( U_{00} \) is the initial voltage of phase A; \( Z_{11}', Z_{22}', Z_{00}' \) are the positive, negative and zero sequence fault equivalent impedances, respectively; \( Z_{11}'', Z_{22}'', Z_{00}'' \) are the impedances of the sending-end side and receiving-end side systems, respectively, which include system impedance and line impedance.

The steady-state short-circuit current supplied by the sending-end side is:

\[
I_{ka} = \frac{1}{3} I_{ka} \left( \frac{Z_{11}'' + Z_{22}''}{Z_{11} + Z_{22} + Z_{00}''} + \frac{Z_{00}'}{Z_{00} + Z_{00}''} \right)
\]  

(23)

In general, the resistance component of the zero sequence impedance is greater than the positive sequence impedance. Hence, the short-circuit current and overvoltage value during the single-phase-to-ground fault is smaller compared with the three-phase-to-ground fault.

### E. Influencing Factors of Short-circuit Faults

For internal short-circuit faults, the position of the severe fault point is influenced by multiple factors. The fault types and the system strength tend to be the crucial ones. The relationship between the position of the severe fault point and equivalent impedance are shown in Fig. 6. It follows that with smaller system equivalent impedance (the greater electrical strength of the system), the severe fault position is closer to the terminals. In addition, the position of the severe single-phase-to-ground fault is closer to the midpoint compared with the three-phase-to-ground fault.

### V. INFLUENCE OF NON-IDEAL FACTORS ON CHARACTERISTICS OF HWLT SYSTEMS

In practical engineering, the long-distance transmission line shows different significant characteristics compared with the ideal analysis results. Several typical non-ideal factors such as line loss, geomorphic environment and line length deviation will be considered in this section. To describe long transmission lines more accurately, a refined line model is presented.

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**Fig. 6.** Relationship between position of severe fault point and equivalent impedance for different types of short-circuit faults.

**Fig. 7.** Curves of terminal voltage amplitudes and phase angles with varied power. (a) Voltage magnitude with varied \( P_2 \). (b) Voltage phase angle with varied \( P_2 \). (c) Voltage magnitude with varied \( Q_2 \). (d) Voltage phase angle with varied \( Q_2 \).

When \( P_2 \) and \( Q_2 \) are in range of the normal operation conditions, the real part of the sending-end voltage is much larger than the imaginary part. From this perspective, voltage magnitude presents a stronger correlation with active power.
$P$, and phase angle presents a stronger correlation with reactive power $Q$. In heavy load conditions, obvious voltage amplitude differences occur between the two terminals because of line loss.

B. Geomorphic and Electromagnetic Environment

The variant topographic and geomorphic conditions primarily affect soil resistivity of the transmission lines which has a greater influence on the line distribution parameters. The earth resistivity appreciably affects the reactance component because it impacts the distribution of the spatial electromagnetic field. By applying Dubanton’s simplified model [21], it is found that the soil resistivity has an impact on the depth of the penetration, and then influences the impedance parameters. The zero sequence impedance is the most affected parameter, and it has a slight influence on the admittance and positive (negative) sequence impedance. Therefore, the soil resistivity primarily influences the HWLT system during three-phase asymmetric operation conditions.

In addition, if there are other transmission lines nearby, the electromagnetic interaction between these lines will affect the distribution parameters. It has obvious influences on the HWLT line when the horizontal distance is close to the adjacent lines. The effect on the mutual-impedance and mutual-admittance is even more pronounced [22].

C. Deviation of Line Length

Due to the limitation of certain power transmission corridors, the length of the HWLT line is difficult to completely match the accurate half wavelength. Because of the length deviations, charging reactive power and reactive power loss cannot reach balance and this brings radical changes in the voltage loss between the two terminals. By taking the line length from 2800 km to 3100 km, the voltage loss varies for different active power transmissions as shown in Fig. 8.

![Fig. 8. Voltage loss varying with length for different active power transmissions ($P_2 = 0$).](image)

Voltage loss varies with the length change for different power factors as shown in Fig. 9. With the increase line length, voltage loss presents a trend of increasing in positive power factor condition ($P_2$ and $Q_2$ are in the same transmission direction). On the other hand, with the increase of line length, voltage loss presents a trend of decreasing in negative power factor conditions ($P_2$ and $Q_2$ are in the opposite transmission direction).

![Fig. 9. Voltage loss varying with length for different power factors ($P_2 = 1$).](image)

D. Refined Model of HWLT Lines

Due to non-ideal factors mentioned above, the total line cannot be regarded as a uniform transmission line. According to the parameter variation, the HWLT line can be divided into several subsections in a series. The influence of non-ideal factors on the HWLT line is described by segmentation more accurately.

By applying the refined model, given the receiving-end voltage and current, the sending-end voltage and current can be solved by (24) and (25).

\[
\begin{bmatrix}
\dot{U}_1 \\
\dot{I}_1 \\
\dot{U}_2 \\
\dot{I}_2 \\
\end{bmatrix} =
\begin{bmatrix}
\phi(I_1) & \phi(I_2) & \cdots & \phi(I_n) \\
\end{bmatrix}
\begin{bmatrix}
\dot{U}_2 \\
\dot{I}_2 \\
\end{bmatrix}
\]

\[
\phi(I_n) = \begin{bmatrix}
\cosh(\gamma_n l_n) & Z_n \sinh(\gamma_n l_n) \\
\sinh(\gamma_n l_n) & Z_n \cosh(\gamma_n l_n) \\
\end{bmatrix}
\]

where $\gamma_n$, $Z_n$, $I_n$ are the propagation coefficient, characteristic impedance and length of each line subsection, respectively.

VI. CASE STUDY

Based on the existing power system structure in China, a 1000 kV HWLT line from Zhundong to northern Anhui is established. The steady-state and fault characteristics are analyzed using simulation software and comparing the results with the mechanism explanation conclusion above.

The steady-state voltage characteristics are calculated by the PSD-BPA software. The fault characteristics are simulat-
ed by the ATP-EMTP software. In the electromagnetic transient simulation, the Bergeron model is adopted and the step size is 0.1 ms. The results of the node voltages are obtained by using the fast Fourier transform algorithm to extract the power frequency component.

A. Simulation Results Under Normal Operating Conditions

The voltage profiles along the HWLT line for different active power and power factors are depicted in Fig. 10 and Fig. 11. The peak voltage increases with the increase of the transmitted active power or the decrease of the power factor which is similar to the theoretical analysis results. The SIL is approximately 4500 MW in this case. There is a decrease in the voltage on the 3600 MW loading and conversely, voltage rises in the middle when the transmitted power exceeds 4500 MW as shown in Fig. 10. In terms of reactive power flow within the HWLT line, when the active power is lower than the SIL, the middle parts of the line absorb the reactive power from two sides and this presents a voltage dip. Conversely, when the transmitted power exceeds the SIL, reactive power flows from the middle to the two sides and arouses a voltage rise in the middle. Due to the line loss, the receiving-end voltage is lower than the sending-end voltage.

B. Simulation Results for Different Faults

The equivalent impedances of sending-end system and receiving-end system are $Z_1 = (0.00009+j0.005652)$ p.u. and $Z_2 = (0.00003+j0.002605)$ p.u., respectively. Fault points are at 0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, and 3000 km, respectively. The fault settings are as follows:

1) Single-phase-to-ground instantaneous fault. It occurs at 0 ms and at 100 ms, the phase A is tripped at the terminals (this instantaneous fault is extinguished at 100 ms). The re-closing is applied at 1200 ms.

2) Three-phase permanent fault. It occurs at 0 s and the terminals of the line are tripped at 100 ms.

The maximum voltage magnitudes for different fault positions based on the electromagnetic transient simulation are shown in Fig. 12(a).

There are two severe fault points which respectively locate at 200 km and 2800 km caused by a three-phase fault. As for the single-phase short-circuit fault, the severe fault points are at 400 km and 2600 km. The maximum voltage magnitude for the three-phase fault is about 7.4 p.u. and 3.3 p.u. for the single-phase fault. The calculation results by the-
oretical circuit analysis are shown in Fig. 12(b). Comparing these two figures, the distribution regularities of the maximum voltage magnitudes and severe fault positions have certain similarities. But the voltage profiles based on steady-state circuit analysis appear to have a more serious overvoltage compared with the electromagnetic transient results.

In fault conditions, the electromagnetic wave reflection process along the HWLT line may last 0.8 to 1.0 s to reach steady state. It means that line tripping operations have a greater influence on the voltage peak value. More accurate results can be obtained from the electromagnetic transient simulation. Aiming at the overvoltage problem, from grid operation perspective, the fast line tripping setting in fault condition makes a greater contribution to decrease the overvoltage value. For grid planning, [23] shows that a proper configuration of the metal oxide arrester (MOA) and suitable insulation coordination can make a greater contribution to suppress the switching overvoltage.

For fault conditions, the voltage comparison results are shown in Table II. Generally, the maximum voltage magnitudes of the refined model are 2%-5% higher than the ideal model, especially for short-circuit faults, and the voltage deviation is more obvious. Therefore, in order to describe the HWLT line more precisely in actual engineering analysis, it is necessary to build a refined line model considering non-ideal factors.

C. Simulation Results Considering Non-ideal Factors

Taking the Zhundong to northern Anhui transmission corridor as an example, as presented in Appendix A Fig. A1, it passes through the Tien Shan Mountains, Ala Shan Desert, Loess Plateau, and North China Plain. The great elevation and climate deviation increase the differences in the parameters of the transmission lines. The transmission corridor is divided into four subsections based on geographical positions. The line length and sequence measured parameters of each subsection are shown in Appendix A Table AII.

The steady-state voltage comparison results between the refined line model and the ideal line model are shown in Table I. \( E_r \) and \( E_s \) represent the error rates of sending-end voltage and maximum voltage, respectively. Keeping the receiving-end voltage 1000 kV constant, the voltage of the sending end has a 20-50 kV variation between the two models. There are considerable deviations up to 5.66% error of the maximum voltage.

### TABLE I

| Transmitted active power (MW) | Transmitted reactive power (Mvar) | Sending-end voltage (kV) | Maximum voltage (kV) |
|------------------------------|-----------------------------------|-------------------------|----------------------|
|                              | Ideal model                       | Refined model           | Ideal model          | Refined model          |
| 0                            | 0                                 | 1000.7                  | 1034.3               | 3.35                  |
| 1500                         | 0                                 | 1013.3                  | 1046.9               | 3.31                  |
| 3000                         | 0                                 | 1025.8                  | 1060.0               | 3.33                  |
| 4500                         | 0                                 | 1038.3                  | 1073.4               | 3.38                  |
| 6000                         | 0                                 | 1050.9                  | 1087.2               | 3.45                  |
| 4500                         | 500                               | 1038.3                  | 1066.7               | 2.73                  |
| 4500                         | 1000                              | 1038.3                  | 1059.9               | 2.08                  |
| 4500                         | −1000                             | 1038.4                  | 1087.1               | 4.69                  |

\( E_r \) and \( E_s \) represent the error rates of sending-end voltage and maximum voltage, respectively. Keeping the receiving-end voltage 1000 kV constant, the voltage of the sending end has a 20-50 kV variation between the two models. There are considerable deviations up to 5.66% error of the maximum voltage.

### TABLE II

| Fault type            | Line model | Peak value (p.u.) | Fault point (km) |
|-----------------------|------------|-------------------|------------------|
| Load-rejection        | Ideal      | 1.06              | 0                |
|                       | Refined    | 1.08              | 0                |
| Three-phase-to-ground | Ideal      | 8.43              | 230              |
|                       | Refined    | 8.81              | 220              |
| Single-phase-to-ground| Ideal      | 3.87              | 280              |
|                       | Refined    | 3.97              | 270              |

### VII. CONCLUSION

The voltage characteristics of the HWLT line for both steady-state and fault conditions are systematically analyzed and explained by the wave process in this paper. Main conclusions are as follows.

1) Voltage profiles along the HWLT line are significantly affected by the transmitted active power and power factor. The peak voltage value increases with the increase of active power or the decrease of the power factor. Compared with the conventional UHV transmission line, more severe partial overvoltage caused by a low-power factor will happen along the HWLT line.

2) The obvious power frequency overvoltage will not take place during the load-rejection process. However, for the internal short-circuit fault, series resonance overvoltage occurs in certain fault positions when approximately 100 to 400 km from the terminals. The most serious overvoltage happens at 1500 km away from the fault point and its maximum magnitude is up to 7.5 p.u. for the three-phase-to-ground fault or 3.5 p.u. for the single-phase-to-ground fault, respectively.

3) Geomorphic conditions and electromagnetic environments influence the line parameters which cannot be ignored. It arouses 2%-6% errors in maximum voltage magnitudes for steady-state or fault conditions. These non-ideal factors need to be considered according to the practical engineering environment utilizing a refined transmission line model.
APPENDIX A

PARAMETERS OF LGJ-8×500 TYPE OVERHEAD LINE

| Sequence | r (Ω/km) | joL (Ω/km) | c (μF/km) |
|----------|----------|------------|-----------|
| Positive | 0.00629  | 0.2614     | 0.01396   |
| Zero     | 0.17522  | 0.9449     | 0.00822   |
| Positive | 0.00619  | 0.2704     | 0.01359   |
| Zero     | 0.20300  | 0.9114     | 0.00914   |
| Positive | 0.00626  | 0.2591     | 0.01409   |
| Zero     | 0.17969  | 0.9459     | 0.00828   |
| Positive | 0.00611  | 0.2571     | 0.01483   |
| Zero     | 0.17348  | 0.9356     | 0.00936   |

Fig. A1. Transmission corridor of Zhundong to northern Anhui HWLT simulation scenario.

TABLE AII

PARAMETERS OF UHV TRANSMISSION LINES

| No. | Length (km) | Sequence | r (Ω/km) | joL (Ω/km) | c (μF/km) |
|-----|-------------|----------|----------|------------|-----------|
| 1   | 869         | Positive | 0.00629  | 0.2614     | 0.01396   |
|     |             | Zero     | 0.17522  | 0.9449     | 0.00822   |
| 2   | 685         | Positive | 0.00619  | 0.2704     | 0.01359   |
|     |             | Zero     | 0.20300  | 0.9114     | 0.00914   |
| 3   | 728         | Positive | 0.00626  | 0.2591     | 0.01409   |
|     |             | Zero     | 0.17969  | 0.9459     | 0.00828   |
| 4   | 648         | Positive | 0.00611  | 0.2571     | 0.01483   |
|     |             | Zero     | 0.17348  | 0.9356     | 0.00936   |

REFERENCES

[1] Y. Cao, Q. Li, Y. Tan et al., “A comprehensive review of Energy Internet: basic concept, operation and planning methods, and research prospects,” Journal of Modern Power Systems and Clean Energy, vol. 6, no. 1, pp. 398-411, May 2018.
[2] S. Chen and C. Liu, “From demand response to transaction energy: state of the art,” Journal of Modern Power Systems and Clean Energy, vol. 6, no. 1, pp. 10-21, Jan. 2017.
[3] Y. Zhu, L. Jia, C. Duan et al., “Status of testing field for ocean energy generation,” Journal of Modern Power Systems and Clean Energy, vol. 6, pp. 20-32, Feb. 2017.
[4] D. Huang, Y. Shu, J. Ruan et al., “Ultra high voltage transmission in China: developments, current status and future prospects,” Proceedings of the IEEE, vol. 97, no. 3, pp. 154-162, Mar. 2009.
[5] G. Samorodov, S. Kandakov, S. Zilberman et al., “Technical and economic comparison between direct current and high-voltage transmission systems for very long distances,” IET Generation, Transmission and Distribution, vol. 11, no. 11, pp. 2871-2879, Sept. 2017.
[6] F. V. Lopes, B. F. Küssel, K. M. Silva et al., “Fault location on transmission lines little longer than half-wavelength,” Electric Power Systems Research, vol. 114, pp. 101-109, Sept. 2014.
[7] A. A. Wolf and O. V. Shcherbacov, “On normal working conditions of compensated lines with half-wave characteristic,” Elektrichesko, vol. 1, pp. 147-158, Jan. 1940.
[8] F. J. Hubert and M. R. Gent, “Half-wavelength power transmission lines,” IEEE Transactions on Power Apparatus and Systems, vol. 84, no. 10, pp. 965-974, Oct. 1965.

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