International Journal of Grid Distribution Computing
Vol.7, no.3 (2014), pp.155-162
http://dx.doi.org/10.14257/ijgdc.2014.7.3.15

# Power Balance Protection Using Long-distance Discretization Equation for EHV Transmission Lines

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## Abstract

*Based on the distribution parameters equation of long-distance transmission lines, which is expressed in phasor form, the paper proposes a discretization equation model, analyzes the protection of EHV transmission lines with shunt reactors by applying power balance principle and then the power balance protection criterion is determined. The power balance protection method, which is based on discretization equation of long-distance transmission lines, maximizes the use of the fault information such as voltage and current, etc. In this way, the fault of EHV transmission lines with shunt reactors can be removed accurately and quickly. On the other hand, this method is more convenient for modern microprocessor protection to process the discrete data and improve the power system performance after the criterion of power balance protection is determined. Results of EMTP simulation have demonstrated that under various fault conditions of EHV transmission lines with shunt reactors the power balance protection method has higher sensitivity and reliability and can be applied to identify the internal or external fault correctly.*

**Keywords:** *discretization equation, power balance protection, EHV, transmission lines, protection criterion*

## 1. Introduction

When certain fault of EHV transmission lines with shunt reactors arises, due to influence of reactor inductance and distributed capacitance of long-distance transmission lines, transient process of power system becomes extremely complex[1-2]. Through the assumption of linear distribution of instantaneous voltage and current, and through the special treatment for protection criterion discretization, "Energy balance protection" calculates the energy of transmission lines which is input over a period of time, compares and judges the internal or external fault by using two different methods[3-5]. Hence, referring to "energy balance" thought, based on certain model, it is feasible and necessary to explore a new protection method for long-distance EHV transmission lines with shunt reactors whose fault information of current and voltage is contained after certain fault occurs.

Based on the distribution parameters equation of long-distance transmission lines, the paper proposes a discretization equation model, analyzes the protection of EHV transmission lines with shunt reactors by applying power balance principle and then the power balance protection criterion is determined. The power balance protection method, which is based on discretization equation of long-distance transmission lines, maximizes the use of the fault information such as voltage and current, *etc.*, in this way, the fault of EHV transmission lines with shunt reactors can be removed accurately and quickly. On the other hand, this method is

ISSN: 2005-4262 IJGDC

more convenient for modern microprocessor protection to process the discrete data and improve the power system performance after the criterion of power balance protection is determined.

## 2. Direct Discretization Equation for Long-distance Transmission Lines

In the modern era of microcomputer relay protection, discrete data is commonly used, accurate calculation is needed or distribution parameters of long-distance transmission system can be considered. In this condition, the traditional lumped parameter model and the long-distance transmission lines equations expressed in phasor form can hardly meet the research requirements. Correspondingly, the long-distance transmission lines equations based on distributed parameter model is used in the derivation of power system parameters [6-8].

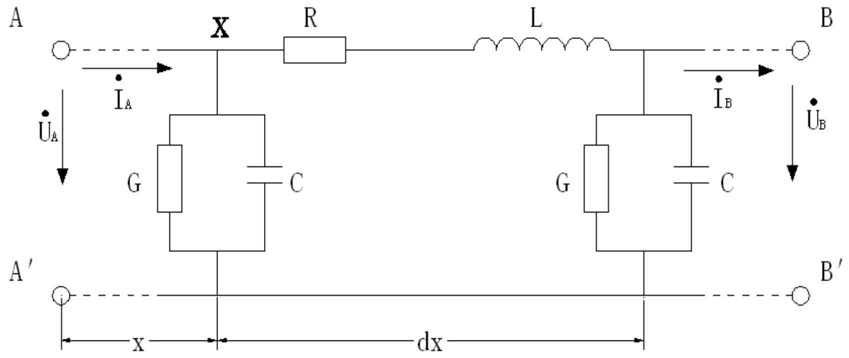


**Figure 1. Electric Circuit Model for Long-distance Transmission Lines**

As is shown in Figure 1, the voltage and current of point "X" on long-distance transmission lines, whose distance from side A to point "X" is roughly x kilometers, can be expressed by long-distance transmission lines equations as follows:

$$\begin{cases} \dot{U}_X = \dot{U}_A \cosh(\gamma x) - Z_c \dot{I}_A \sinh(\gamma x) \\ \dot{I}_X = \dot{I}_A \cosh(\gamma x) - \dfrac{\dot{U}_A}{Z_c} \sinh(\gamma x) \end{cases} \tag{1}$$

Considering side B, the voltage and current of point "X" can also be expressed as follows:

$$\begin{cases} \dot{U}_X = \dot{U}_B \cosh(\gamma x) + Z_c \dot{I}_B \sinh(\gamma x) \\ \dot{I}_X = \dot{I}_B \cosh(\gamma x) + \dfrac{\dot{U}_B}{Z_c} \sinh(\gamma x) \end{cases} \tag{2}$$

Where $\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$ is the propagation constant; $Z_c = \sqrt{\dfrac{R + j\omega L}{G + j\omega C}}$ is the characteristic impedance.

Setting $\gamma = \alpha + j\beta$ , $Z_c = f + jg$ , using properties of hyperbolic, $\dot{U}_X$ in equation (1) can be derived as follows:

$$\begin{aligned}\dot{U}_X &= \dot{U}_A\left[\cosh(\alpha x)\cos(\beta x) + j\sinh(\alpha x)\sin(\beta x)\right] - \dot{I}_A(f + jg)\left[\sinh(\alpha x)\cos(\beta x) + j\cosh(\alpha x)\sin(\beta x)\right]\\ &= \dot{U}_A\cosh(\alpha x)\cos(\beta x) + j\dot{U}_A\sinh(\alpha x)\sin(\beta x) - \dot{I}_A\left[\sinh(\alpha x)\cos(\beta x) - g\cosh(\alpha x)\sin(\beta x)\right]\\ &\quad - j\dot{I}_A\left[f\cosh(\alpha x)\sin(\beta x) + g\sinh(\alpha x)\cos(\beta x)\right]\\ &= \dot{U}_A\cdot PA + j\dot{U}_A\cdot PB - \dot{I}_A\cdot PM - j\dot{I}_A\cdot PN\end{aligned} \tag{3}$$

Similarly, $\dot{I}_X$ in equation (1) can be derived as follows:

$$\dot{I}_X = \dot{I}_A\cdot PA + j\dot{I}_A\cdot PB - \dot{U}_A\cdot PE - j\dot{U}_A\cdot PF \tag{4}$$

Where, $PA = \cosh(\alpha x)\cos(\beta x)$,

$PB = \sinh(\alpha x)\sin(\beta x)$,

$PM = f\sinh(\alpha x)\cos(\beta x) - g\sin(\beta x)\cosh(\alpha x)$,

$PN = f\sin(\beta x)\cosh(\alpha x) + g\sinh(\alpha x)\cos(\beta x)$,

$PE = \dfrac{f\sinh(\alpha x)\cos(\beta x) + g\sin(\beta x)\cosh(\alpha x)}{f^2 + g^2}$,

$PF = \dfrac{f\sin(\beta x)\cosh(\alpha x) - g\sinh(\alpha x)\cos(\beta x)}{f^2 + g^2}$.

Since $j = e^{j\frac{\pi}{2}} = \cos(\frac{\pi}{2}) + j\sin(\frac{\pi}{2}) = j$, after reduction, equation (3) and (4) can be written as:

$$\begin{cases}\dot{U}_X = \dot{U}_A\cdot PA + \dot{U}_A\cdot e^{j\frac{\pi}{2}}\cdot PB - \dot{I}_A\cdot PM - \dot{I}_A\cdot e^{j\frac{\pi}{2}}\cdot PN\\ \dot{I}_X = \dot{I}_A\cdot PA + \dot{I}_A\cdot e^{j\frac{\pi}{2}}\cdot PB - \dot{U}_A\cdot PE - \dot{U}_A\cdot e^{j\frac{\pi}{2}}\cdot PF\end{cases}$$

With the discretization, the above equations can be expressed as:

$$\begin{cases}u_{X(k)} = PA\cdot u_{A(k)} + PB\cdot u_{A(k+n)} - PM\cdot i_{A(k)} - PN\cdot i_{A(k+n)}\\ i_{X(k)} = PA\cdot i_{A(k)} + PB\cdot i_{A(k+n)} - PE\cdot u_{A(k)} - PF\cdot u_{A(k+n)}\end{cases} \tag{5}$$

The above equations are direct discretization equation for long-distance transmission lines based on the distributed parameter model. Where, $n = \frac{1}{4}N$ , and N represents sampling points in one power frequency cycle.

After analysis and simulation, it is found that although the accuracy of direct discretization equation for long-distance transmission lines in transient process whose voltage has dramatic change is less than in steady-state process, overall, the accuracy difference in the two processes is relatively smaller. Therefore, the direct discretization equation for long-distance transmission lines can be used to track the voltage variation. And for current, regardless of the transient process whose change of current is relatively severer or in steady-state process whose change of current is relatively more stable, the accuracy of direct discretization equation is relatively higher and it can well reflect the variation of the current.

# 3. Power Balance Protection Method for EHV Transmission Lines

Because of higher voltage level and longer working distance for EHV transmission lines, when some power system fault occurs the transient process is more complex, and especially when shunt reactors are used the complexity of transient process is exacerbated. To improve the security and stability of power system, based on the direct discretization equation for long-distance transmission lines, rapid and sensitive relay protection for EHV transmission systems can be achieved by applying power balance protection principle on both sides of the transmission lines [9-10].

## 3.1. Principle of Power Balance Protection

For one EHV transmission line, based on direct discretization equation for long-distance transmission lines, the electrical parameters on one side can be derived from the electrical parameters on the other side.

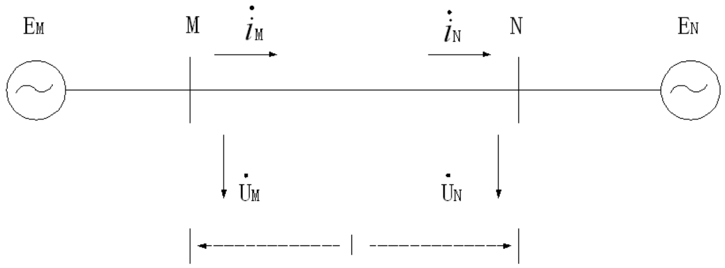


Figure 2. Simplified Model for Long-distance EHV Transmission Lines

Therefore, from Figure 2, equation (6) as follows can be obtained.

$$\begin{cases} \dot{u}_N = \dot{u}_M \cosh(\gamma l) - \dot{i}_M \sinh(\gamma l) \\ \dot{i}_N = \dot{i}_M \cosh(\gamma l) - \dfrac{\dot{u}_M}{Z_c} \sinh(\gamma l) \end{cases} \tag{6}$$

As is shown in Figure 2, for segment "MN" of the protected transmission line, according to the long-distance transmission lines equations, electric parameters $u_{N(t)}$ and $i_{N(t)}$ of side N can be deduced from the measured electrical parameters $u_{M(t)}$ and $i_{M(t)}$ of side M. The deduced parameters are expected to be equal to the measured parameters $u'_{N(t)}$ and $i'_{N(t)}$ of side N. That can be written as:

$$\begin{cases} u_{N(t)} = u'_{N(t)} \\ i_{N(t)} = i'_{N(t)} \end{cases} \tag{7}$$

Here, setting $P_{NN} = u_N * i_N$ as the measured power at side N, and $P_{MN} = u_N * i_N$ as the deduced power of side N from side M, when no fault occurs in the protection zone, even though certain fault occurs outside the segment "MN" of the protected transmission line, equation (7) is always true. Therefore equation (8) as follows can be obtained.

$$P_{MN} = u_N \cdot i_N = P_{NN} = u'_N \cdot i'_N \tag{8}$$

When a fault occurs in protection zone of transmission line, equation (6) is no longer valid, and then equation (7) and (8) are no longer valid. Correspondingly, the power balance of side N and side M cannot be maintained. Therefore, whether a fault occurs or not in segment "MN" of transmission line can be judged by working condition where power balance of both sides can be maintained or not, and the protection of transmission line can be enforced sequentially.

### 3.2. Criterion Determination of Power Balance Protection

Nowadays, because large scale discrete data are used in modern microcomputer protection, based on the direct discretization equation for long-distance transmission lines, equation (8) can be written in discrete form as follows:

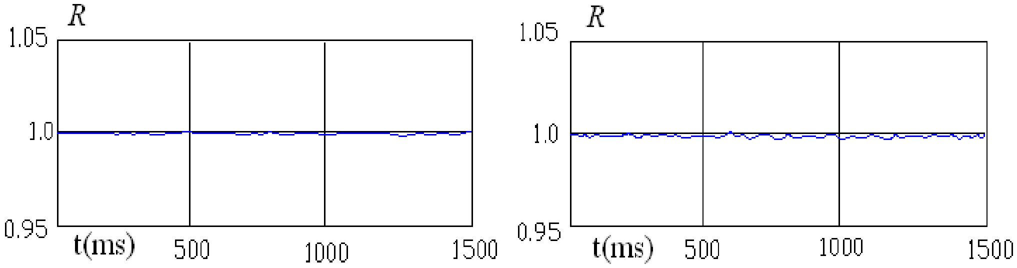
$$P_{MN}(k) = u'_N(k) \cdot i'_N(k)$$

$$P_{NN}(k) = u_N(k) \cdot i_N(k)$$

$$P_1 = \frac{W_1}{T} = \frac{1}{T}\sum_{k=N_1}^{N_1+\Delta N} P_{MN}(k)$$

$$P_2 = \frac{W_2}{T} = \frac{1}{T}\sum_{k=N_1}^{N_1+\Delta N} P_{NN}(k)$$

Setting $R = \frac{P_1}{P_2} = \frac{W_1}{W_2}$, for $P_{MN}(t)$ and $P_{NN}(t)$, if no fault occurs in the protection zone of segment "MN", even when certain fault occurs outside the segment "MN", theoretically there is always $P_{MN}(t) = P_{NN}(t)$, and then, $|W_1| = |W_2|$, so $R = 1$ and $|1 - R| = 0$. After EMTP simulation, the values of "R" in two cases can be obtained, which are shown in Figure 3.



**(a) Fault-free in Protection Zone** **(b) Fault Occurs in Protection Zone**

**Figure 3. R's Value for Transmission Lines of "MN" in Working Condition**

Figure 3 shows there is $R \approx 1$ even some fault occurs outside the segment "MN". So, under this condition the protection device can correctly judge without any misoperation. On the contrary, no matter how much the transition resistance value is, if some fault occurs in the protection zone of segment "MN" there is always $P_{MN}(t) \neq P_{NN}(t)$ theoretically, and then, $|W_1| \neq |W_2|$, so $R \neq 1$ and $|1 - R| > 0$.

Taking into account all kinds factors affecting the practical application, such as calculation error, the criterion equation (9) as follows can be obtained.

$$\left|1 - R\right| = R_s \geq R_{set} \tag{9}$$

Where $R_{set}$ is the protection criterion, to determine its value, the sensitivity and reliability of protection are to be considered? So, the appropriate value of protection criterion can be calculated based on simulation model whose transmission line of "MN" has different transition resistance and no fault occurs within the segment "MN". The criterion values under different transition resistance are shown in Table 1.

**Table 1. Criterion Values for $R_{set}$ Under Different Transition Resistance**

| Transition Resistance（Ω） | 1 | 50 | 100 | 300 | 500 | 700 | ∞ ( Fault-free） |
|---|---|---|---|---|---|---|---|
| R | 3 | 1 | 1 | 0.6 | 0.5 | 0.35 | 0 |

As can be seen from Table 1, in the fault-free case, the value of R is zero. However, in the case of faults even with larger transitional resistance, the value of R is still much larger than the value "0". Therefore, giving attention to the sensitivity and reliability of protective system, the appropriate value of $R_{set}$ can be selected as protection criterion of transmission line of "MN".

For protection criterion $\left|1 - R\right| = \left|1 - \frac{W_1}{W_2}\right| = R_s \geq R_{set}$, after further derivation, equation (10) as follows can be obtained.

$$\left|1 - R\right| = \left|1 - \frac{W_1}{W_2}\right| = \left|1 - \frac{U'_N I'_N \cos(\theta_M)}{U_N I_N \cos(\theta_N)}\right| = \left|1 - \frac{P_{MN} \cos(\theta_M)}{P_{NN} \cos(\theta_N)}\right| = R_s \geq R_{set} \tag{10}$$

As can be seen from the above equation, the protection criterion is power amplitude function as well as phase function. That is to say, the criterion not only has the function of amplitude comparison, but also has the function of phase comparison.

For the protected segment "MN" of transmission line, the direction of actual flowing current of side M and side N has the following two cases.

(1) under the same direction of actual flowing current on both sides.

In this case, according to "Law of Energy Conservation", if certain fault occurs in the segment "MN" of transmission line, there must be $\left|W_1\right| \neq \left|W_2\right|$ and $\left|1 - R\right| = R_s > 0$. Therefore, by setting and choosing appropriate value of $R_{set}$, the fault in some range of impedance can be confirmed. That is to say, the power amplitude changes can be confirmed as a protection criterion of transmission line of "MN".

(2) Under the opposite direction of actual flowing current on both sides.

As can be seen from equation (10), if the direction of actual flowing current of side M and side N is opposite to each other, then $\cos(\theta_M)$ and $\cos(\theta_N)$ are also opposite. Thereby, the value of $R_s$ is increased, which speeds up the action of protection device and is advantageous for transmission line protection.

Based on data of the protection principle of power balance, lots of relay protect simulation are executed by combining with EMTP. The results of simulation have demonstrated that, under various fault conditions of EHV transmission lines with shunt reactors, the power balance protection method has higher sensitivity and reliability and can be applied to identify the internal or external faults correctly.

## 4. Conclusion

Nowadays, the EHV transmission lines undertake large number electric energy exchange and transmission tasks, and its safe and stable operation plays an important role in power systems. When certain fault of EHV transmission lines with shunt reactors arises, due to influence of reactor inductance and distributed capacitance of long-distance transmission lines, transient process of power system becomes extremely complex. Power balance protection method, which is based on discretization equation of long-distance transmission lines, maximizes the use of the fault information such as voltage and current, etc, and the faults of EHV transmission lines with shunt reactors can be removed accurately and quickly. On the other hand, this method is more convenient for modern microprocessor protection to process discrete data and improve the power system performance after the criterion of power balance protection is determined.

## Acknowledgements

We would like to acknowledge that this work has been supported by “the Fundamental Research Funds for the Central Universities” (3142013065).

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