A NEW APPROACH FOR THE CALCULATION OF DISTURBING CURRENTS IN INDUCTIVELY COUPLED TRANSMISSION LINES

Christian RAUNIG, Ernst SCHMAUTZER,
Lothar FICKERT, Andreas STEINKELLNER
Graz, University of Technology – Austria
christian.raunig@TUGraz.at, schmautzer@TUGraz.at,
lothar.fickert@TUGraz.at, andreas.steinkellner@TUGraz.at

Georg ACHLEITNER
Austrian Power Grid – Austria
georg.achleitner@apg.at

ABSTRACT

In this paper the authors present measurements, calculations and results of the optimization of transposition schemes and phase configurations of transmission lines in a region in Austria regarding inductively coupled transmission lines. Different development states of the power circuit and variants under economic and realizable practical conditions are presented. The calculations were performed with a new calculation method combining the node potential method and a chain-ladder model for coupled line conductors to calculate the inductive influence and unbalance currents (zero-sequence currents) of extended transmission line circuits in normal operation mode.

The presented method allows the calculation of unbalance currents and the effects of inductive coupling for a given network scenario with a coupled transmission line model. The investigation of these disturbance currents lead to an optimized transposition scheme considering economic aspects (reduced number of transposition towers at predefined places, small zero-sequence currents, etc.). With this method existing grids can be optimized by reducing circulating currents. Also extension strategies and decisions for the integration of new transformer substations and different grid configurations can be provided.

INTRODUCTION

Disturbing circulating currents caused by mutual inductive coupling in transmission line circuits can lead to undesired alarm messages, causing a reduction of the transport capacity of the lines, additional losses, voltage and other distortions and operation problems.

Because of these reasons investigations and optimizations of the phase configurations and transposition schemes have to be performed to reduce the problems that can be caused through disturbing currents.

One reason for the occurrence of unbalance currents is the looping of new transformer stations into an existing symmetric transmission line configuration, e.g. for the connection of wind power farms or additional grid support. Before the integration the line was balanced very well by transposing the phases in optimal places. This balancing effect of the transposition is lost caused by the looping and an electrical asymmetry will occur. As a result of the asymmetry and the inductive coupling effects circulating currents will have an impact on the network operation.

MODELLING

Based on the self-impedance and mutual-impedance between conductors with earth return, described in [1...4, 6], a realistic model of inductively coupled line circuits was developed. A mathematical model for the description of the mutual coupling between two conductors with earth return [5] is used. To include the realistic effects of the reduction of a multiple grounded earth wire or cable shield, the chain ladder model in combination with the node potential method, which is well-known for load flow calculations [6], was chosen. The simulations give realistic results even if other simulation programs have convergence problems.

Basically, the inductive coupling between conductors can be simulated by impedance-quadripoles. Mathematically the phase-to-earth loops with consideration of the mutual coupling between the conductors can be simplified described with the following relation (1).

$$\begin{vmatrix} \Delta \underline{\mathbf{U}}_A \\ \Delta \underline{\mathbf{U}}_B \end{vmatrix} = \begin{vmatrix} \underline{\mathbf{Z}}_{AA} & \underline{\mathbf{Z}}_{AB} \\ \underline{\mathbf{Z}}_{BA} & \underline{\mathbf{Z}}_{BB} \end{vmatrix} \cdot \begin{vmatrix} \underline{\mathbf{I}}_A \\ \underline{\mathbf{I}}_B \end{vmatrix} \qquad (1)$$

Due to the symmetry: $\underline{\mathbf{Z}}_{AB} = \underline{\mathbf{Z}}_{BA}$.

In Fig. 1 the fundamental illustration of two inductively coupled phases (phase-to-earth loops) is shown.

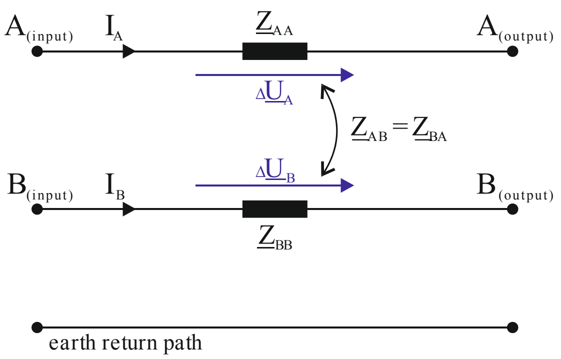

Figure 1: Fundamental illustation of two inductively coupled phases; $\underline{Z}_{AA}$, $\underline{Z}_{BB}$… self-impedance; $\underline{Z}_{AB}$, $\underline{Z}_{BA}$… mutual impedance; $A_{(input)}$, $A_{(output)}$… input and output nodes of the nodes auf the quadripole

To describe the fundamental relationship between two inductively coupled phase-to-earth loops a mathematical model according to E. Clarke [5] can be applied. The transfer-impedances between the terminals of that basic circuit (quadripole), consisting of phase-to-earth loops with consideration of the mutual coupling between the conductors, can be determined with (2…5).

Pole $A_{(input)}$ – Pole $A_{(output)}$
$$\underline{Z}_{AA} - \frac{\underline{Z}_{AB}^2}{\underline{Z}_{BB}} \quad (2)$$

Pole $B_{(input)}$ – Pole $B_{(output)}$
$$\underline{Z}_{BB} - \frac{\underline{Z}_{AB}^2}{\underline{Z}_{AA}} \quad (3)$$

Pole $A_{(input)}$ – Pole $B_{(input)}$ or Pole $A_{(output)}$ – Pole $B_{(output)}$
$$\frac{\underline{Z}_{AA} \cdot \underline{Z}_{BB} - \underline{Z}_{AB}^2}{\underline{Z}_{AB}} \quad (4)$$

Pole $A_{(input)}$ – Pole $B_{(output)}$ or Pole $B_{(input)}$ – Pole $A_{(output)}$
$$-\frac{\underline{Z}_{AA} \cdot \underline{Z}_{BB} - \underline{Z}_{AB}^2}{\underline{Z}_{AB}} \quad (5)$$

In Fig. 2 an equivalent network which describes the applied mathematical equivalent of two mutual coupled phase-to-earth loops is shown

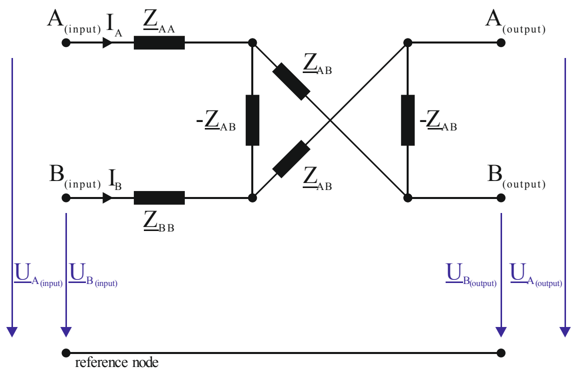

Figure 2: Applied mathematical equivalent circuit of two coupled phases (phase-to-earth loops) according to E. Clarke [5]

This presented equivalent circuit corresponds to a quadripole with the transfer impedances (2…5) between the different poles (see Fig. 2) and can be calculated with the self- and mutual impedances of the phase-to-earth loops [5]. This model can be used for the preparation of the required relations for the node potential method that is applied in the presented calculation model. For the holistic modeling of a multiple three-phase circuit power line with ground wires the individual mutual couplings between the involved conductors, earth wires, reduction conductors, cable shields, single side grounded conductors etc. are replaced by this presented equivalent circuit. To simulate transmission lines the individual (different) line sections (e.g. span fields) of that region have to be cascaded.
This new simulation model provided in this paper, allows a detailed simulation of inductively coupled conductor arrangements e.g. overhead transmission line or high voltage cable line circuits. The further calculation steps are based on the calculation of the nodal analysis and can be achieved by simple matrix multiplications [6].

GRID CONFIGURATION

The presented investigations are performed on transmission overhead lines in a region of Austria with different grid extension states.
The area contains of several transmission lines between substations that are routed parallel on the same towers or in close vicinity together. In the substations the different lines are connected through bus bars. The different grid extension states include the integration of new transformer substations along the existing lines and planned grid extensions in the coming years.

RESULTS

The aim of the investigations is to calculate and minimize the circulating currents in the high voltage power circuit caused by inductive coupling. During operation of the power circuit alarm messages occurred because the level of the circulating currents exceeds the given alarm level of 120 A of the substation control and protection system.
As a classification for the level of the circulating currents the following colour code is used:
- Green (0 – 50 A)
- Orange (50 – 100 A)
- Red (> 100 A)

To get realistic results the calculations were performed with real load states that have been provided by the grid operator. At the occurrence of typical load states problems with circulating currents (zero-sequence alarm messages) in the grid occurred.
The first calculation results of the model with the basic extension state (Fig. 3) were compared to performed measurements.

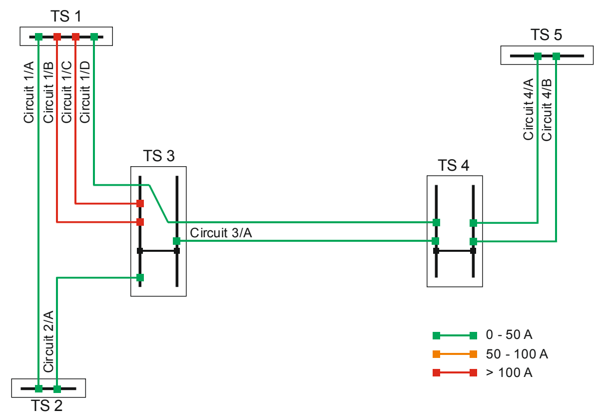

Figure 3: Illustration of the analyzed transmission line area in Austria, extension state no. I, basic version

Comparison: Measurements - Calculations

For the verification of the model one of the measurement results of a typical load state was recalculated. The calculated results from the model are compared with the measurements to get an indication about the accuracy of the model.

In table 1 the comparison between the calculated and the measured values are presented.

Transmission line circuit	Circulating current in A	
	Measured	Calculated
Circuit 1/B	199	185
Circuit 1/C	159	154
Circuit 1/D	36	44

Table 1 Comparison between measured and calculated results with a selected load state

The calculation results are quite in good agreement with the measured values.

Calculations results

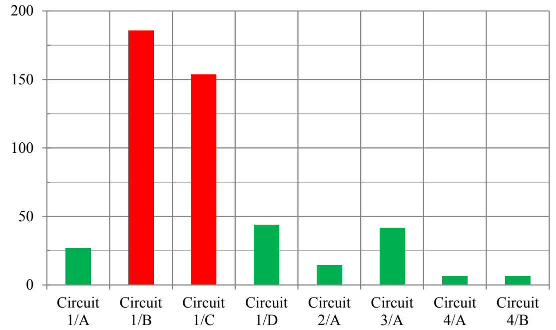

Figure 4: Calculation results of the ciruclating currents in A, extension state I

The results from the extension state I (Fig. 4) show that especially the "short" circuits of the quad line circuits carry a high level of circulating currents.
In the following figures some selected calculation results of different extension states are shown:

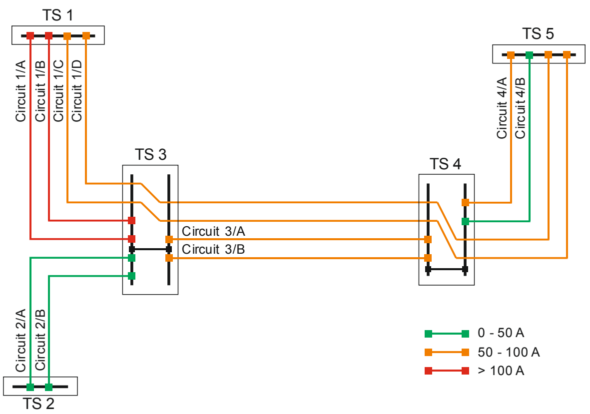

Figure 5: Illustration of the analyzed transmission line area, extension state no. II, with higher transport potential

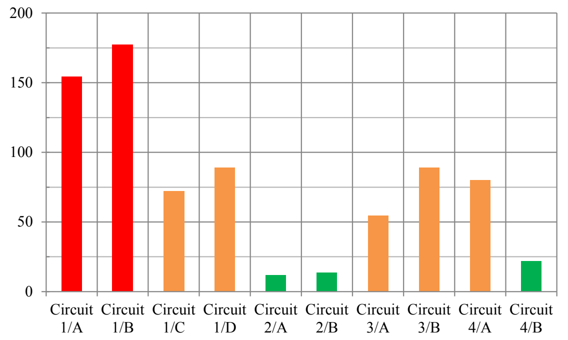

Figure 6: Calculation results of the ciruclating currents in A, extension state II

It can be seen in figure 6 that with an additional grid extension the level of circulating currents in the grid area rise extremely. This can be explaned through the higher asymmetry and the additional circuits whithout an optimized transposition or phase configuration.

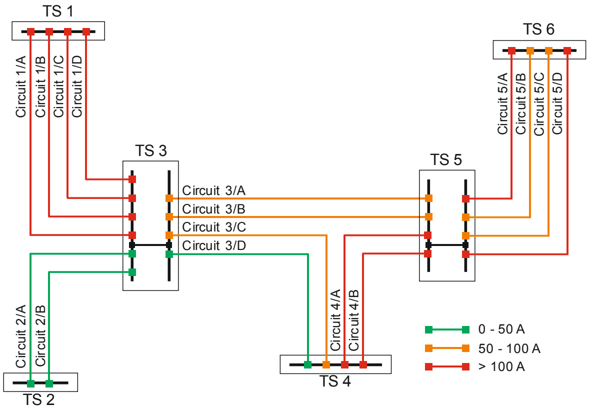

Figure 7: Illustration of the analyzed transmission line area, extension state no. III, final version

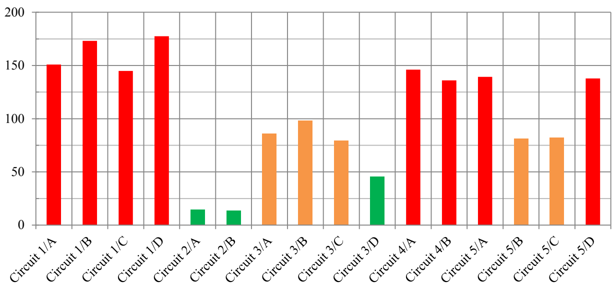

Figure 8: Calculation results of the ciruclating currents in A, extension state III

Fig. 8 shows that the level of the induced circulating currents for the extension state no. III is very high. Most of the line circuits exceed the given level of 120 A of the substation control and protection system and alarm messages occur.

Optimization

To reduce the effects of the mutual inductive coupling and the circulating currents the line circuits have to be electrically balanced. This balancing can be achieved through a new or an adopted transposition scheme.
In accordance with the grid operator individual sections for balancing the high voltage power circuits were identified concerning economic and practical aspects (existing transposition towers etc.).
The investigation of these disturbance currents result in an optimized transposition scheme considering economic aspects (reduced number of transposition towers at predefined places, low circulating currents, etc.). In the following figures the impact of that section-wise optimization is shown. For all optimizations the same three optimization areas with the same phase configuration are used (Fig. 9 and Fig. 10).

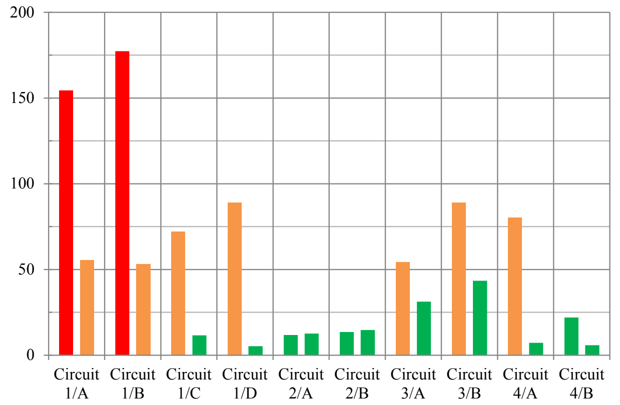

Figure 9: Comparision of the calculated results of the ciruclating currents in A for the original (left side) and optimized (right side) transposition, extension state II

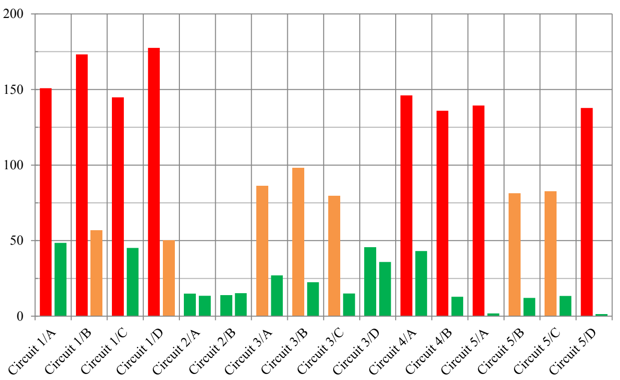

Figure 10: Comparision of the calculated results of the ciruclating currents in A for the original (left side) and optimized (right side) transposition, extension state III

Because of economic aspects only the phase configuration (phase position) was optimized and not the entire line transposition scheme.

CONCLUSION

Disturbing circulating currents typically result from geometrical unbalances of the line conductors, mutual inductive coupling effects and unbalanced load currents. Through the additional integration of new transformer stations, grid extension etc. into an existing line scheme the originally balanced transposition scheme of the line is lost and disturbance currents can occur.
The presented method shows a possibility for the calculation of disturbance currents with the help of a realistic inductively coupled line model. Furthermore optimizations of the line transposition are possible to reduce the negative effects of the mutual coupling between the transmission lines.
With the help of the investigations it is possible to reduce the induced circulating currents by changing the transposition on a small number of selected areas in the grid with respect to economic and practicable aspects.
The optimization results show, that a reduction of the expected circulating currents up to 90 % is possible.

REFERENCES

[1] J. R. Carson, Oct. 1926, "Wave propagation in overhead wires with ground return", *Bell Syst. Tech. J.*, vol. 5, pp. 539-56.

[2] F. Pollaczek, 1926, "Über das Feld einer unendlich langen wechselstromdurchflossenen Einfachleitung", *E. N. T.*, vol. 3, no. 9, pp. 339-359.

[3] G. Haberland, 1926, "Theorie der Leitung von Wechselstrom durch die Erde", *Zeitschrift für Angewandte Mathematik und Mechanik*, vol. 6, pp. 366-379.

[4] ITU, 2005, *Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines*, ITU-T, ISBN: 92-61-03941-3.

[5] E. Clarke, 1950, *Circuit Analysis of A-C Power Systems*, John Wiley & Sons, New York, USA.

[6] D. Oeding, B.R. Oswald, 2011, *Elektrisch Kraftwerke und Netze*, 7th Edition, Springer-Verlag, Berlin, Germany.

[7] E. Schmautzer, 1991, *Ein Beitrag zur Berechnung der niederfrequenten induktiven Beeinflussung von Rohrleitungsnetzen,* Dissertation, Graz University of Technology, Graz, Austria.

[8] A. Steinkellner, 2012, *Der Einfluss der Verdrillung auf die Stromunsymmetrie bei induktiv gekoppelten Hochspannungsfreileitungssystemen,* Thesis, Graz University of Technology, Graz, Austria.

[9] C. Raunig, unpublished, *Modellierung und Beeinflussung durch induktive und kapazitive Kopplung von Drehstromsystemen auf andere leitende Strukturen,* Ph.D. Dissertation, Graz University of Technology, Graz, Austria.