DOI: 10.19279/TVZ.PD.2019-7-4-16

EQUATION SYSTEM CONCEPT FOR COMPUTATION OF GROUND FAULT CURRENT DISTRIBUTION WITH ELECTROMAGNETIC MODEL

KONCEPT SUSTAVA JEDNADŽBI ZA IZRAČUN RASPODJELE STRUJE ZEMLJOSPOJA ELEKTROMAGNETSKIM MODELOM

Zdenko Balaž, Krešimir Meštrović

Tehničko veleučilište u Zagrebu, Vrbik 8, Zagreb, Hrvatska

ABSTRACT

This paper describes the new equations system concept of electromagnetic model for computation of ground fault current distribution in electric power substations. We developed the new electromagnetic model based on applying the finite element technique to an integral equation formulation in the frequency domain. Model components can be located in homogeneous soil or in air. Model can take into account complete electromagnetic coupling between its components. Using known ground fault currents of adjacent substations, from which power substation hit by ground fault is supplied, in each of the adjacent substations one or more equivalent three-phase voltage sources are formed. Based on developed theoretical background, we also developed a software package, which is primarily designed for computation of ground fault current distribution. However, this software package can also be used for advanced analysis of current and voltage conditions on overhead power lines and underground power cables as illustrated by the examples.

Keywords: *electromagnetic coupling, electromagnetic model, electric power substations, finite element technique, ground fault current distribution*

SAŽETAK

Rad opisuje novi koncept sustava jednadžbi elektromagnetskog modela za izračun struje zemljospoja u transformatorskim stanicama. Razvili smo novi elektromagnetski model koji se temelji na primjeni tehnike konačnih elemenata na integralnu formulaciju jednadžbi u frekvencijskoj domeni. Elektromagnetske komponente modela mogu se nalaziti u homogenom tlu ili u zraku. Model može uzeti u obzir kompletnu elektromagnetsku spregu između njegovih komponenti. Koristeći poznate vrijednosti struja zemljospoja susjednih transformatorskih stanica, iz kojih se napaja mjesto kvara, u svakoj od susjednih trafostanica formira se ekvivalentni jednofazni ili trofazni naponski izvor. Na temelju razvijene teorijske pozadine, razvili smo i programski paket, koji je prvenstveno namijenjen za izračunavanje raspodjele struja zemljospoja. Ovaj programski paket može se koristiti i za napredne analize strujnih i naponskih prilika na nadzemnim vodovima i podzemnim energetskim kabelima kako je prikazano u primjerima.

Ključne riječi: *elektromagnetski model, elektromagnetska veza, metoda konačnih elemenata, raspodjela struje zemljospoja, transformatorske stanice*

1. INTRODUCTION

1. UVOD

A lot of efficient computation factors, such as transformer station ground bars, transformers, metal limbs, ground bars and protecting cables for overhead power lines, power lines monitors, bare conductors over cables and other visible parts should be taken into consideration when a more accurate computation of ground current distribution is needed.

For example, in legislation like IEEE Std.; 80-2000, ITU-T 270-9; HRN HD 637 S1 and others, ground fault current distribution is estimated roughly by means of graphs or calculated approximately by means of simple analytical expressions. Even some software packages do not take into account the very important conductive coupling between transformer station ground bars, overhead cable ground bars and all other conductive parts which are in direct contact with the ground.

Applying the final element technique, an original numerical model is developed based on potential knots method. Such a model includes an overall electromagnetic coupling (conductive, capacitive and inductive) between all components and it is called electromagnetic model for computation of ground fault current distribution [1, 2].

2. EQUATION SYSTEMS OF ELECTROMAGNETIC MODEL

2. SUSTAV JEDNADŽBI ZA ELEKTROMAGNETSKI MODEL

2.1. LOCAL SYSTEM OF EQUATIONS FOR CONDUCTIVE AND CAPACITIVE COUPLINGS

2.1. LOKALNI SUSTAV JEDNADŽBI ZA KONDUKTIVNE I KAPACITIVNE VEZE

In the electromagnetic model there are conductive and capacitive coupled cylindrical sections guide, (bare and insulated conductors buried), equivalent metal plates, (groundings of substation and transmission line limbs). In a two-layer medium (air and homogenous soil), they have a complete local system of equations for transverse currents:

$$\left[\overline{Y}^{p}\right]\cdot\left\{\overline{\Phi}\right\}=\left\{\overline{I}^{pc}\right\} \tag{1}$$

$$\left[\overline{Y}^{p}\right]=\left[A^{p}\right]^{T}\cdot\left[\overline{Z}^{p}\right]^{-1}\cdot\left[A^{p}\right] \tag{2}$$

where:

$\left[\overline{Y}^{p}\right]$ -matrix of own and transversal local admittance nodes of conductive and capacitive couplings of the final element,

$\left\{\overline{\Phi}\right\}$ - potential vector of final element local nodes which are formed by all conductive and capacitive couplings of electromagnetic model

$\left\{\overline{I}^{p}\right\}$ - transversal current vector of final element local nodes formed by conductive and capacitive couplings of the final element

$\left[\overline{Z}^{p}\right]$ - own matrix and transversal impedance of conductive and capacitive couplings of the final element

$\left[A^{p}\right]$ - matrix of transversal connection between final element couplings and their local nodes

According to the final elements technique, from the local equation system (1) an incomplete local equation system is following for local nodes transversal current of conductive and capacitive couplings of the final element which is:

$$\left[\overline{Y}^{p}\right]\cdot\left\{\overline{\Phi}\right\}=\left\{0\right\} \tag{3}$$

2.2. LOCAL EQUATION SYSTEM OF INDUCTIVE COUPLED COMPONENTS

2.2. LOKALNI SUSTAV JEDNADŽBI ZA INDUKTIVNE VEZE

In electromagnetic model only cylindrical conductor segments are coupled inductively (bare conductors in the ground or in the air and cables buried in the ground) and in two layer means formed by the air and homogenous ground, complete local equation system for transversal currents is, [3-6]:

$$\left[\overline{Y}^{u}\right]\cdot\left\{\overline{\Phi}\right\}=\left\{\overline{I}^{u}\right\} \tag{4}$$

$$\left[\overline{Y}^{u}\right]=\left[A^{u}\right]^{T}\cdot\left[\overline{Z}^{u}\right]^{-1}\cdot\left[A^{u}\right] \tag{5}$$

where:

$\left\{\overline{\Phi}\right\}$ - matrix of own and interrelated local nodes longitudinal admittances final element inductive coupled components,

$\left\{\overline{\Phi}\right\}$ - potential vector of final element local nodes formed by interrelated inductive coupled components of the final element,

$\left[\overline{Z}^{u}\right]$ - longitudinal currents vector of final element local nodes which is formed by interrelated inductive coupled components of electromagnetic model,

$\left[\overline{Z}^{u}\right]$ - matrix of own and interrelated longitudinal impedances of the final element inductive coupled components,

$\left[A^{u}\right]$ - matrix of longitudinal connection between inductive coupled components of the final element and their local nodes.

An incomplete local equation system for local nodes longitudinal currents inductively coupled components of the final element is:

$$\left[\overline{Y}^{u}\right]\cdot\left\{\overline{\Phi}\right\}=\left\{0\right\} \tag{6}$$

If computation using other algorhythm for ground fault currents are required which flow through phase conductors or just the zero components of these currents, then an incomplete equation local system is as follows:

$$\left[\overline{Y}^{u}\right]\cdot\left\{\overline{\Phi}\right\}=\left[A^{u}\right]^{T}\cdot\left[\overline{Z}^{u}\right]^{-1}\cdot\left[\overline{Z}^{\mathfrak{s}}\right]\cdot\left\{\overline{I}^{f}\right\}=\left\{\overline{I}^{d}\right\} \tag{7}$$

where:

$\left\{\overline{\Phi}\right\}$ - matrix of own and interrelated local nodes longitudinal admittances final element inductive coupled components without phase conductors,

$\left\{\overline{\Phi}\right\}$ - potential vector of final element local nodes formed by interrelated inductive coupled components of the final element,

$\left[\overline{Z}^{u}\right]$ - own and interrelated longitudinal impedances of inductive coupled components of the final element without phase conductors,

$\left[A^{u}\right]$ - matrix of the longitudinal connection between inductive coupled components of the final element and their local nodes without phase conductors,

$\left[\overline{Z}^{\mathfrak{s}}\right]$ - matrix of the interrelated longitudinal impedances between phase conductors and other inductive coupled components of the observed final element,

$\left\{\overline{I}^{f}\right\}$ - vector of the known longitudinal currents of the phase conductors through which ground fault currents flow,

$\left\{\overline{I}^{d}\right\}$ - current sources contribution vector obtained due to inductive coupling of phase conductors and other components of the final element.

If the known ground fault currents are introduced into the calculation of ground fault current distribution, then given independent current sources are obtained and there is no need to introduce transformers into electromagnetic model. Inductive coupling between phase conductors through which ground fault currents flow and conductor cylindrical segments of other components of the final element should be taken into consideration, while conductive and capacitive coupling between phase conductors through which ground fault currents flow and conductor cylindrical segments of other final element components should be neglected.

2.3. EQUATION LOCAL SYSTEMS OF EQUIVALENT ELEMENTS

2.3. LOKALNI SUSTAVI JEDNADŽBI NADOMJESNIH ELEMENATA

By using monophase two-winding transformer, it is possible to show how local nodes described by matrix admittance may be obtained from equivalent scheme, Fig.1.

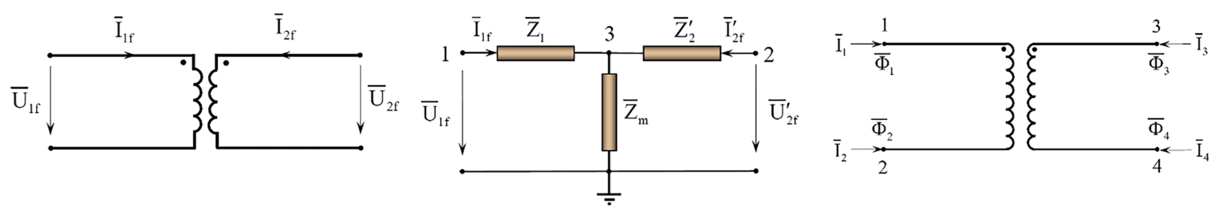

Figure 1 *Equivalent scheme and local nodes of two-winding monophase transformer*

$$\left[\overline{Y}^f\right]\cdot\left\{\overline{\Phi}^f\right\} = \left\{\overline{I}^f\right\} \quad (8)$$

where:

$\left[\overline{Y}^f\right]$ stands for matrix admittance of transformer local nodes,

$\left\{\overline{\Phi}^f\right\}$ is potential vector of transformer local nodes, and

$\left\{\overline{I}^f\right\}$ is current vector of transformer local nodes.

Matrix equation describes the incomplete local equation system:

$$\left[\overline{Y}^f\right]\cdot\left\{\overline{\Phi}^f\right\} = \left\{0\right\} \quad (9)$$

The same principle may be used to describe other parts of the system in electromagnetic model, like equivalent impedance, equivalent symmetrical voltage sources, equivalent loads and others. If for one or more global nodes in default there are applied currents from the outside or some independent power sources, then the global system of equations is completed by the inclusion of those of applied currents into the incomplete global system of equations so that a complete global system of equations is as follows:

$$\left[\overline{Y}^g\right]\cdot\left\{\overline{\Phi}^g\right\}=\left\{\overline{I}^{d}_{g}\right\}+\left\{\overline{I}^{a}_{g}\right\} \quad (10)$$

where:

$\left\{\overline{I}^{a}_{g}\right\}$ - vector of currents applied to global nodes

$\left\{\overline{I}^{d}_{g}\right\}$ - global vector contribution of given voltage and current sources

Except currents applied to global nodes, potentials of some global nodes may be defined. Since the potential of a distant ground in a developed electromagnetic model is zero, it is obligatory to prescribe only the potential of one of the nodes on each equivalent three-phase load connected to the transformer winding which is not directly connected to the central transformer station. The easiest way is to take the prescribed potentials are zero.

Only when in the system of equations, according to the rules of the finite element technique, prescribed potentials of global nodes are included, a modified complete global system of equations whose solutions are potentials of global nodes.

3. COMPUTATION OF GROUND FAULT CURRENT DISTRIBUTION

3. IZRAČUN RASPODJELE STRUJE ZEMLJOSPOJA

The decision of the complete global system of equations to calculate the potentials of all global nodes, using a matrix of connections, makes it easy to determine the potential of local nodes of each finite element, after which distribution of fault current from the local system of equations of finite elements is calculated.. Systems of equations for calculation components of the considered finite element read:

a) for transversal currents (conductive and capacitive coupling)

$$\left\{\overline{I}^p\right\}= \left[\overline{Z}^p\right]^{-1}\cdot\left[A^p\right]\cdot\left\{\overline{\Phi}\right\} \quad (11)$$

for longitudinal currents (inductive coupling)

$$\left\{\overline{I}^u\right\}= \left[\overline{Z}^u\right]^{-1}\cdot\left[A^u\right]\cdot\left\{\overline{\Phi}\right\} \quad (12)$$

for longitudinal currents (inductive coupling with connected independent current sources)

$$\left\{\overline{I}^u\right\} = \left[\overline{Z}^u\right]^{-1}\cdot\left(\left[A^u\right]\cdot\left\{\overline{\Phi}\right\} - \left[\overline{Z}^{f}\right]\cdot\left\{\overline{I}^f\right\}\right) \quad (13)$$

for currents entering into transformer local nodes

$$\left\{\overline{I}^c\right\} = \left[\overline{Y}^t\right]\cdot\left\{\overline{\Phi}\right\} \quad (14)$$

currents entering into local nodes of equivalent impedance

$$\left\{\overline{I}^c\right\} = \left[\overline{Y}\right]\cdot\left\{\overline{\Phi}\right\} \quad (15)$$

for currents entering into local nodes of the voltage source

$$\left\{\overline{I}^c\right\} = \left[\overline{Y}\right]\cdot\left\{\overline{\Phi}\right\} - \left\{\overline{I}^d\right\} \quad (16)$$

for currents entering into local nodes of the symmetrical load

$$\{\bar{I}^{c}\} = [\bar{Y}] \cdot \{\bar{\Phi}\} \qquad (17)$$

where:

$\{\bar{I}\}$ - current vectors entering the local nodes

$\{\bar{\Phi}\}$ - vector potential of local nodes

$[\bar{Z}]$ - matrix of own and interrelated impedances

$[A]$ - matrix of local nodes admittance

$[A]$ - matrix connections between final element elements and their local nodes

4. EXAMPLE
4. PRIMJER

According to the developed electromagnetic model an example is selected where circular plate grounding is used for grounding substation and limbs. For single core cables, conductor of transmission lines, protective and grounding cables, cylindrical segments are used.

For the selected model equivalent one node impedances are introduced as well as three-phase power sources and the given prime potentials. These components represent the input data of the developed software tool. It is chosen and processed, as an example, for the distribution area along the substation 110/35/10 (20) kV Drniš, in Croatia, Fig. 2., which is presented by a one pole scheme built with 1957 components that have 868 global nodes and the same number of linear equations. All together there are 8001 input data.

Electromagnetic model replaces, (representing in reality), 560 power facilities, the area of a portion of Distribution System Operator HEP, whose surface is 3,031 square km and has about 83,368 customers. After calculating for this purpose originally developed computer program, [1, 2] 3136 output data are obtained.

The results obtained by the computer program, have been checked by some other commercial computer programs. What this model rises above the rest, is its effectiveness for a large number of input parameters and the accuracy of the included conductive coupling.

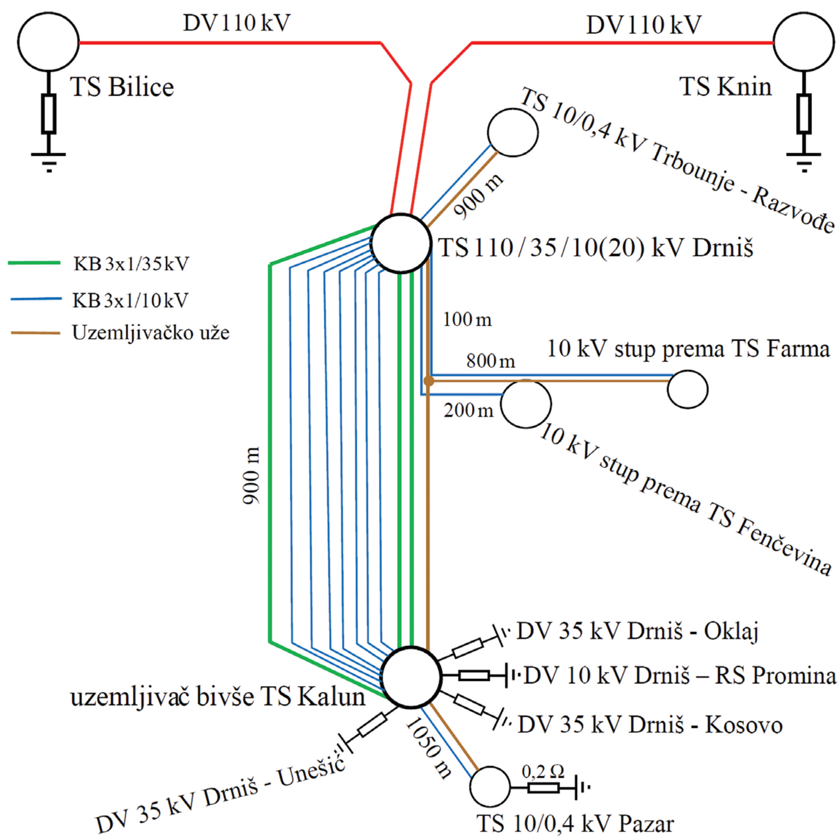

***Figure 2** Distribution area along the substation 110/35/10 (20) kV Drniš, in Croatia*

The computer program was previously tested even in a study for the Croatian transmission system operator, where 231 examples of operating conditions were processed, as well as failures and works on 35kV, 110kV and 220kV aerial lines, cable lines and submarine cables, [7].

5. CONCLUSION
5. ZAKLJUČAK

Developed electromagnetic model and calculations carried by developed original program result in conclusions that suggest applications in power systems for which it is possible to make decisions regarding similar problems. Perception and understanding of the issue concerned are similar to those of an expert computer system, (mechanism of inference, database and knowledge base), which can be viewed as a design aid. Presentation material processing, graphically shown clearly points to the specific operating conditions, but its database is available for all other processing which include analysis and synthesis of similar examples.

Although the design is not an invention or a discovery, the presented modeling process that is understood as designing with concrete results is an original work. Universal use is proven because it can be modeled by any new or existing power plant unit, but also their electromagnetic conditions in the whole system. Modeling can be considered as designing a system that comes down to prototype when real or simulated power components for any mode are implemented. As such it is an excellent tool for testing or maintenance planning in large power systems. Although with excellent results, based on the experience, issues of new guidelines and legislation as well as intellectual property are opened concerning such expert computer processes, i.e. over designing tools.

6. REFERENCE
6. REFERENCES

[1.] Balaž Z.: Elektromagnetski model za izračun raspodjele struje zemljospoja, Sveučilište u Splitu, Fakultet elektrotehnike, strojarstva i brodogradnje, Doktorska disertacija, Split, 2015.

[2.] Balaž Z.; Meštrović K.: Inteligentni i ekspertni sustavi u elektroenergetici, Tehničko veleučilište u Zagrebu, uUdžbenik, Zagreb, 2015.

[3.] Vujević S.; Balaž Z.; Modrić T.; Sarajčev P.: Hybrid Model for Analysis of Ground Fault Current Distribution; International Review of Electrical Engineering (IREE), Vol. 7, No. 3, pp. 4035-4045, 2012.

[4.] Sarajčev, P.: Elektromagnetski model sustava vodiča u višeslojnom sredstvu, , Sveučilište u Splitu, Fakultet elektrotehnike, strojarstva i brodogradnje, Split, 2008.

[5.] Vujević, S.; Lovrić, D.; Balaž, Z.; Gaurina, S.: Time-Harmonic Modelling of Two-Winding Transformers Using the Finite Element Technique, International Review on Modelling and Simulations (IREMOS) , 6 (Part B), 1922-1927, 2013.

[6.] Vujević, S.; Balaž, Z.; Modrić, T;, Sarajčev, P.: Hibrid model for Analysis of Ground Fault Current Distribution, International Review of Electrical Engineering, Vol. 7, No. 2, pp. 4035-4045, 2012.

[7.] Vujević, S.; Lucić R.; Jurić-Grgić, I.; Lovrić, D.: Modrić, T.; Balaž, Z.: Izrada pravila i mjera sigurnosti za osiguranje mjesta rada na elektroenergetskim vodovima, Sveučilište u Splitu, Fakultet elektrotehnike, strojarstva i brodogradnje, Split, 2013.

AUTORI · *AUTHORS*

● **Zdenko Balaž -** nepromjenjena biografija nalazi se u časopisu Polytechnic & Design Vol. 4, No. 2, 2016.

Korespondencija · ***Correspondence***
zbalaz@tvz.hr

● **Krešimir Meštrović -** nepromjenjena biografija nalazi se u časopisu Polytechnic & Design Vol. 1, No. 1, 2013.

Korespondencija · ***Correspondence***
kresimir.mestrovic@tvz.hr