ISSN 1068-3712, Russian Electrical Engineering, 2017, Vol. 88, No. 7, pp. 412–415. © Allerton Press, Inc., 2017.
Original Russian Text © A.L. Slavutskii, V.S. Pryanikov, L.A. Slavutskii, 2017, published in Elektrotekhnika, 2017, No. 7, pp. 20–24.

# Simulating the Transients in a Load Node with a Triple-Wound Transformer at Different Voltage Levels

**A. L. Slavutskii[a], *, V. S. Pryanikov[b], and L. A. Slavutskii[b]**

[a]*LLC Unitel Engineering, Moscow, Russia*
[b]*Chuvash State University, Cheboksary, Russia*
**e-mail: journal-elektrotechnika@mail.ru*

Received June 16, 2017

**Abstract**—The transient processes in the load node of a power system, which contains powerful induction motors and triple-wound transformers, are simulated. A technique for transient calculation using direct-current synthetic schemes of electric circuits (Dommel's algorithm) is presented. A dynamic model of an induction motor in the phase domain and a model of a triple-wound transformer based on inductively coupled branches are used taking into account the transformation of voltage levels. It is shown that the mutual influence of different voltage levels in the circuits can be investigated in the phase domain, within one model, and in the course of one simulation process. As an example, we consider a 110/35/10-kV load node that contains an induction motor, a static load, and a reactive power-compensation device in the form of a capacitor on the low-voltage side, as well as power-transmission lines on the medium-voltage side. Dommel's algorithm makes it possible to investigate various types of nonlinear elements in the system and does not impose any restrictions on the waveform and harmonic composition of signals in the model. The algorithm also allows one to change the parameters and configuration of the timing constraints, which increases the range of the modes considered. When simulating the load node in this domain, various types of asymmetry and complex faults can be considered. The model of the induction motor is highly flexible and yields good results when calculating the dynamic modes.

*Keywords*: load node, transients, induction motor, phase domain, triple-wound transformer, method of synthetic scheme

**DOI:** 10.3103/S1068371217070161

To simulate transients in the load nodes of electric and power systems, calculation methods using dynamic models of system elements are employed. A load node, being an electric circuit, can be described under certain assumptions by a system of differential equations according to Kirchhoff's laws [1]. For certain elements, e.g., electric motors, this system includes equations for a mechanical part [2, 3]. Calculation of load nodes with allowance for different voltage levels is complicated by the necessity of taking into account the transformation coefficient. When calculating steady-state processes, this can be done by reducing the dimensions to a single voltage level; this approach, however, cannot be applied to calculate the processes in the time domain. In addition to the transformation coefficient, it is required to take into account the frequency properties of the elements, including those of a power transformer.

In this work, we reduce the transients calculation in an electric circuit to the calculation of direct-current (DC) synthetic schemes [1]; in the foreign literature, this method is also known as "Dommel's algorithm" [4, 5]. This algorithm has a number of advantages in program implementation, which is proved by its wide use in software development. In contrast to the state variable method [6], this algorithm does not require writing differential equations by Kirchhoff's laws and enables a direct transition to DC-circuit equations. The resulting DC-circuit has the same layout as the original one, which makes the method very convenient. The method does not impose any restrictions on the signal waveform and allows one to easily take into account nonlinear characteristics of system elements. It should be noted that this method yields instantaneous currents and voltages in all branches and nodes of a circuit.

The main calculation stages are as follows.

(1) Approximating the differential equations of the circuit elements with the difference equations associated with synthetic (resistive) equivalent circuits.

(2) Synthesizing systems of algebraic equations in accordance with the synthetic equivalent circuits at each time step of the calculation.

(3) Solving the systems of algebraic equations.

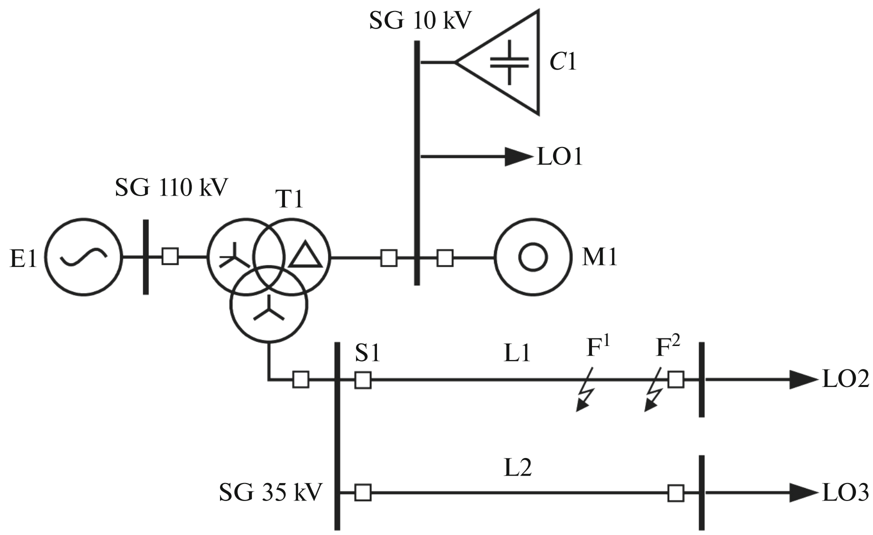


**Fig 1.** Circuit of the load node.

The algorithm is used to calculate transient modes of nonlinear circuits at each time step. First, approximate parameters (currents and voltages) of a resistive (linear) circuit are evaluated; then, using numerical methods for solving systems of nonlinear equations, the refined values of these parameters are found taking into account the nonlinearity of the current–voltage characteristic of the elements [7]. The dimension of the synthesized system of nonlinear equations increases with increasing number of nonlinear elements. Hence, it becomes more difficult to synthesize such a system. For this reason, in this case, the Newton–Raphson method is used to solve the equations of each nonlinear element rather than all equations of a circuit at a time [8].

The model of an induction motor in the phase domain [3] is quite consistent with a three-phase network model, which allows the motor to be connected without additional coordinate transformations [8]. Moreover, simulation in the phase domain proves to be very effective when investigating asymmetrical modes of a multiphase network.

The model of a power transformer consists of inductively coupled branches. During simulation, this allows one to take into account the transformation of voltage levels and vector group of the transformer. A three-phase transformer is regarded as a system of three single-phase transformers. The change in the connection scheme of single-phase transformers allows one to form different vector groups of three-phase transformers.

Figure 1 shows a circuit for a load node with a triple-wound transformer T1 (TDTN-16000/110). The load node includes two 35-kV power-transmission lines (L1 and L2) with loads (LO2 and LO3) at their ends, an electric motor (M1), a static load (LO1), and a reactive power-compensation device in the form of a 10-kV capacitor ($C1$). We simulate an AZMP-5000 powerful induction motor with a fan load. The characteristics of the loads are as follows: $S_{\mathrm{LO1}} = 1$ MB A, $\cos\varphi_{\mathrm{LO1}} = 0.9$, $S_{\mathrm{LO2}} = 5$ MB A, $\cos\varphi_{\mathrm{LO2}} = 0.95$, $S_{\mathrm{LO3}} = 1$ MB A, $\cos\varphi_{\mathrm{LO3}} = 0.95$, power of the compensation device $Q_{C1} = 840$ kV a, and $U_{m1} = \sqrt{2}\times 115$. The parameters of the transformer are taken from its specification. The characteristics of the power-transmission lines are as follows: L1 corresponds to an AC-150/24 wire type, the support type is PB35-1, the length of a U-circuit in the model is 10 km, the number of U-circuits is three, L2 corresponds to an AC-150/24 wire type, the support type is PB35-1, the length of a U-circuit is 50 km, and the number of U-circuits is 1.

The lines were simulated taking into account interphase capacitances, phase–earth capacitance, and mutual inductions among line phase wires. This enables a more detailed analysis of transient modes in the case of earth faults for a network with an insulated neutral. The load node circuit (see Fig. 1) depicts only the switches that are commutated during simulation. The state of the other switches remains unchanged.

Consider the influence on each other among the nodal elements of different voltage classes in the case of successive transients. At the initial instant ($t = 0$ s), motor M1 is plugged in and the node operates in a steady-state mode. At instant $t = 0.2$ s, a single phase-to-earth fault of phase $A$ occurs on line L1 at a distance of 20 km from the system of supply rails. At instant $t = 0.3$ s, a fault between phases $A$ and $C$ occurs at the end of line L1 on the load side. At instant $t = 0.4$ s, line L1 is switched off by switch B1 on the 35-kV rails.

Figure 2a shows that, in the case of an earth fault, the voltage component of phase $A$ (35 kV) with a frequency of 50 Hz decreases by several times. In the

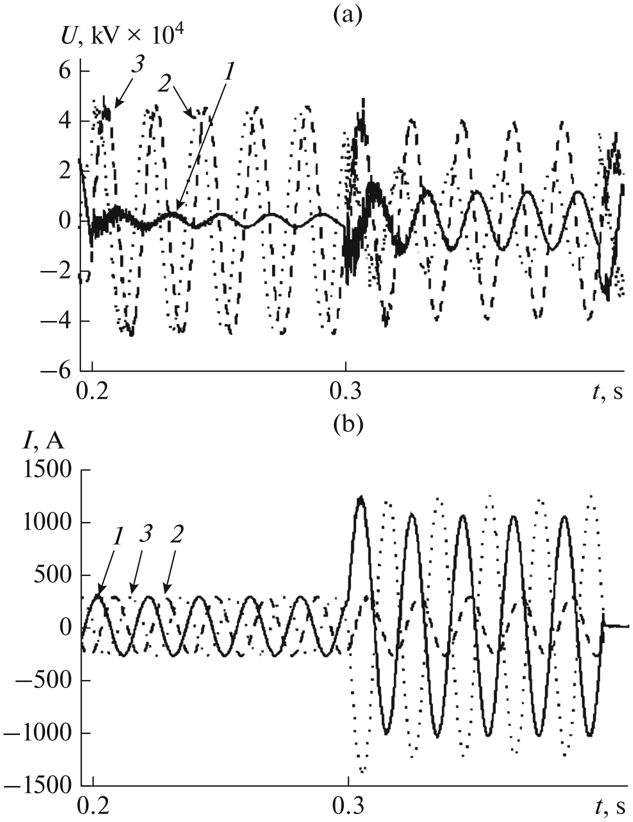


**Fig. 2.** (a) 35 kV Voltage across the rails (phase voltage) and (b) switch current on line L1 (phase designations: (*1*) *A*, (*2*) *B*, and (*3*) *C*).

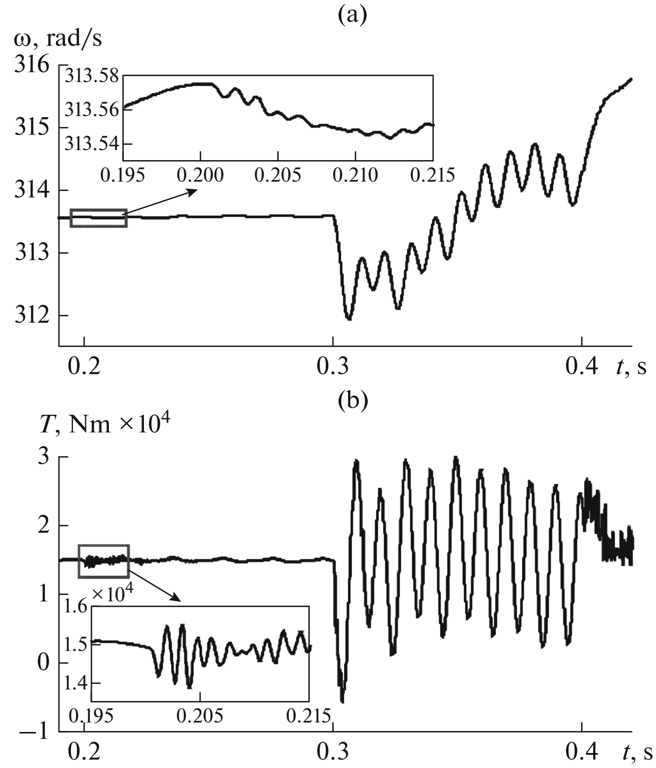


**Fig. 3.** (a) Angular velocity and (b) electromagnetic torque on the motor shaft at the instant of a fault.

fault-free phases, the voltage increases approximately by a factor of 1.73. The potential of the faulted phase approaches that of the earth, but the nominal linear voltage persists.

The voltage across the faulted phase does not decrease to zero at the observation point, as the fault point is spaced at a certain distance. In the faulted and fault-free phases (10 kV), high-frequency oscillations occur. The higher harmonics pass to the 10-kV side via the transformer. When a single-phase fault occurs ($t = 0.2$ s; see Fig. 3), minor perturbations in the angular velocity and electromagnetic torque of the motor show up. Due to the inertia of the mechanical modes of the motor, the perturbations caused by the higher harmonics induced from the medium-voltage side slightly affect the operation of the motor.

In the case of a two-phase fault (see Fig. 2b), the currents in the faulted phases increase significantly. In this case, the directions of the currents become opposite. The current in the fault-free phase changes slightly. The voltage across the fault-free phases (phase voltage) changes both in its angle and in its amplitude (Fig. 2a). The voltage amplitude in phase *A*, on which the earth fault is simulated, increases due to in-feed from phase *C* via the branch of the interphase fault. The voltage across phase *C* decreases. The angle of the voltages across phases *A* and *C* is shifted almost by 180°. In the fault-free phase, the voltage changes its angle but remains close to linear in amplitude.

In the case of an interphase fault in the 35-kV line on the 10-kV side, the phase and amplitude of the voltages change approximately by 10% (see Fig. 4a). The currents in the motor stator change significantly in their angle with the occurrence of harmonic oscillations of their amplitudes (Fig. 4b). This is due to a sharp increase of power flows in the phases on the 35-kV side, which are directed toward the fault. The network elements on the low-voltage side begin to direct their stored energies via the transformer to the faulted segment. The oscillation of the current amplitude and the sharp change in the current direction in the 10-kV rails are due to the fact that the motor (M1) begins to partially operate in a generator mode.

In this mode, the current phases of the motor stator change significantly. Figures 3a (electromagnetic moment) and 3b (angular velocity) show that an interphase fault on line L1 heavily affects the operating mode of the motor. The motor begins to direct its power to the network, whereas the currents in the rotor have no time to change their directions. The current flowing in the stator under the action of the network voltage and the current induced by the rotating magnetic field of the rotor form a joint current of varying

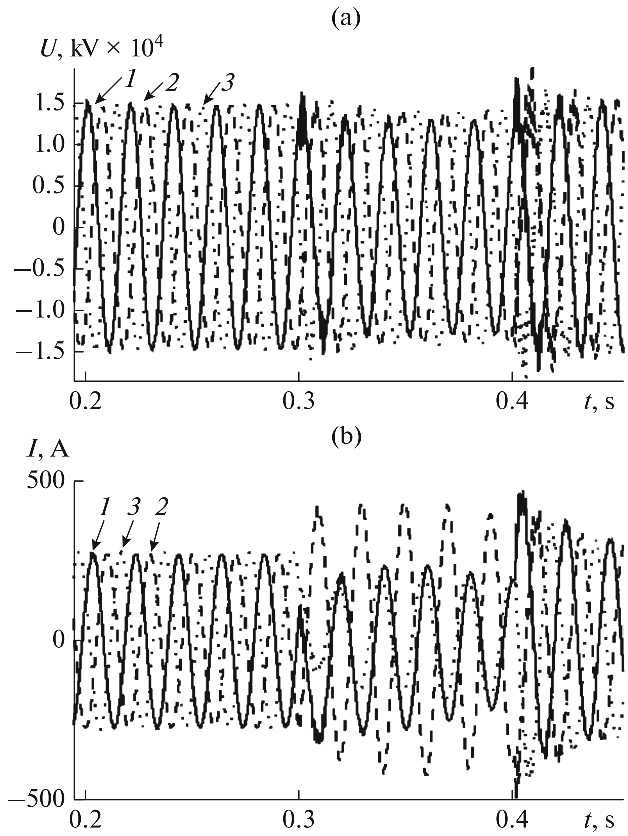


**Fig. 4.** (a) Linear voltages on the low-voltage side and (b) stator currents (phase designations: (*1*) *A*, (*2*) *B*, and (*3*) *C*).

amplitude. The frequency of the induced current differs from that of the network, which also affects the process. The angular velocity and electromagnetic torque oscillate on the second harmonic of commercial frequency. Such processes can cause dangerous mechanical vibrations in the motor, as well as in the mechanisms driven by it. Thus, the proposed technique and models allow one to calculate and analyze the asymmetrical and cascade transients in complex load nodes with triple-wound transformers.

The proposed technique and software [9] can be used to analyze transients in complex load nodes with multiwound transformers and powerful induction motors.

## ACKNOWLEDGMENTS

This work was supported by the Foundation for Promotion of Innovations, contract no. 0033282.

## REFERENCES

1. Butyrin, P.A. and Demirchyan, K.S., *Modelirovnie i mashinnyi raschet elektricheskikh tsepei: uchebnoe posobie* (Simulation and PC Calculation of Electrical Circuits. Student’s Book), Moscow: Vysshaya shkola, 1988.
2. Krause, P.C., Wasynczuk, O., and Sudhoff, S.D., *Analysis of the Machinery and Drive Systems,* New York: IEEE PRESS, 2002.
3. Vinogradov, A.B., *Vektornoe upravlenie elektroprivodami peremennogo toka (Vector Control for AC Electric Drives)*, Ivanovo: Ivanovo Power Engineering Univ., 2008.
4. Dommel, H.W., Digital computer solution of electromagnetic transients in single- and multiphase networks, *IEEE Trans. PAS,* 1969, vol. PAS-88, no. 4.
5. Watson, N. and Arillaga, J., *Power System Electromagnetic Transients Simulation,* London: The Institution of Engineering and Technology, 2007.
6. Chernin, A.B. and Losev, S.B., *Raschet elektromagnitnykh perekhodnykh protsessov dlya releinoi zashchity na liniyakh bol’shoi protyazhennosti (The Way to Calculate Electromagnetic Transient Processes of Relay Protection for Longitude Lines)*, Moscow: Energiya, 1972.
7. Wang, L., Jatskevich, J., Dinavahi, V., et al., Method of interfacing rotating machine models in transient simulation programs, *IEEE Tras. Power Deliv.,* 2010, vol. 25, no. 2.
8. Slavutskii, A.L., The way to consider the residual magnetization in transformer under transient processes simulation, *Vestn. Chuvashsk. Univ.,* 2015, no. 1.
9. Slavutskii, A.L., Russian Inventor’s Certificate no. 2015616968, 2015.

*Translated by Yu. Kornienko*