Journal of Engineering and Applied Sciences 11 (5): 1128-1135, 2016
ISSN: 1816-949X


# A Mathematical Model of the Distribution Transformer Substation in Matlab Simulink

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**Abstract:** The study describes a mathematical model of the Distribution Transformer Substation (DTS) created in MATLAB with using Simulink and SimPowerSystems libraries. Five typical DTS cells were identified with their schemes of main circuits and a list of items. An electrical scheme of model DTS was composed and Simulink model was built on this base. The power and data inputs and outputs in subsystems were considered, as well as disconnectors realization with main blades and earthing switches. Problems of disconnector blocking were discussed. The proposed model allows to analyze DTS operation modes considering measurement, signalization and control circuits of circuit breakers and disconnectors. A DTS operations modes and typical commutations in it were modelled.

**Key words:** Mathematical model, distribution transformer substation, cell, subsystem, disconnector, circuit breaker, blocking, measurement

## INTRODUCTION

Currently, the search for new solutions in relay protection and automatic of electric power systems is proceeding. For middle voltage distribution substations it is advisable to develop microprocessor-based centralized systems of control, relay protection and automatization what can realize all advantages of modern computer technics. At the first stage of this development, it is necessary to build mathematical model of distribution substation and simulate steady state and transient operation modes to determine values of main operational parameters (currents, voltages, power). Such model can be created with software for calculation and analysis of electrical power systems such as Simulation and Model-Based Design (2014) and Power Transmission System Planning Software (2014), etc. However, this software may consider only general high voltage equipment while relay protection research requires consideration of measurement, signalization and control circuits of circuit breakers and disconnectors.

For this reason, it was proposed to build mathematical model of the distribution transformer substation in MATLAB with using Simulink and SimPowerSystems libraries. These libraries contain wide range of electrotechnical, logic, mathematical elements which allows realizing power section of DTS as well as control, measurement and signalization circuits. Moreover, in Simulink a relay protection system for DTS can be built with integration into DTS mathematical model. As a result, we can provide comprehensive research of substation fault operation modes and behavior of relay protection system during these modes.

## MATERIALS AND METHODS

First of all, let’s consider a list of high voltage electrotechnical equipment of distribution substation that should be represented in mathematical model. DTS is an electrical installation which is divided into sections and consists of busbars, a certain number of cells and control passage. In the cells, electrical equipment is mounted: circuit breakers, current transformers, power transformers, line and bus disconnectors, high voltage fuses, voltage transformers, overvoltage protection devices (surge arresters). An analysis of distribution transformer substations typical projects, developed for different applications and real electrical schemes of DTS shows that five typical types of cells can be distinguished:

- Input cell (supply line)
- Outgoing line cell
- Voltage transformer cell

The project is implemented within Federal Targeted Programme for Research and Development in Priority Areas of Development of the Russian Scientific and Technological Complex for 2014-2020. The unique identifier RFMEFI57715X0194, agreement No. 14.577.21.0194 from 10.27.2015.

- Intersection circuit breaker cell
- Power transformer cell

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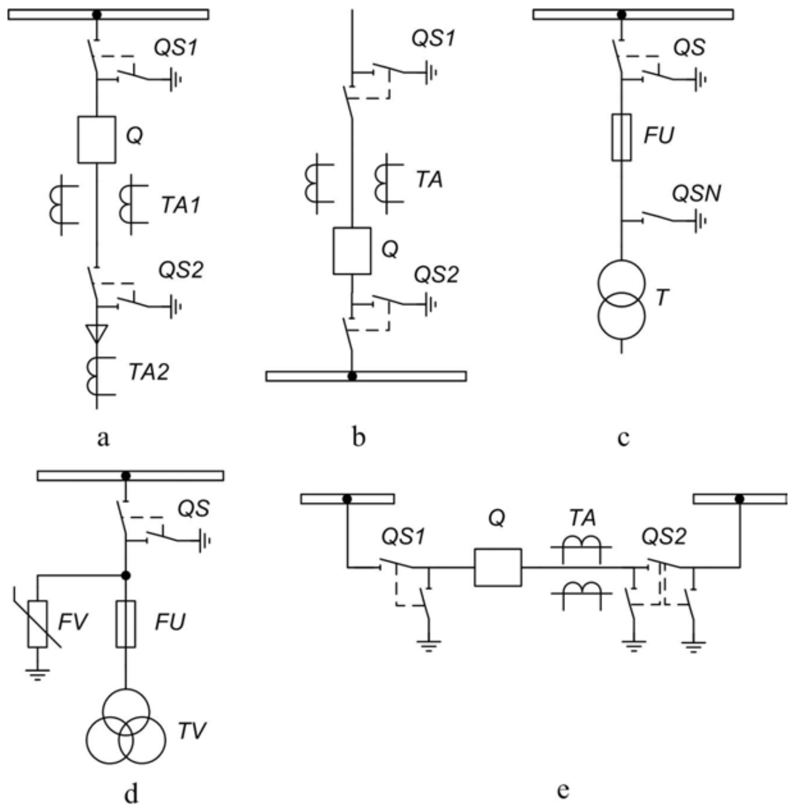


Fig. 1: Electrical schemes of power circuits for outgoing line cell: a) input cell; b) power transformer cell; c) voltage transformer cell; d) intersection circuit breaker cell and e) of DTS

Table 1: List of high voltage equipment of DTS cells

| Name | Conventional designation |
|---|---|
| **Outgoing line cell** | |
| Bus disconnector | QS1 |
| Circuit breaker | Q |
| Current transformer | TA1 |
| Line disconnector | QS2 |
| Zero sequence current transformer | TA2 |
| **Input cell** | |
| Line disconnector | QS1 |
| Current transformer | TA |
| Circuit breaker | Q |
| Bus disconnector | QS2 |
| **Power transformer cell** | |
| Bus disconnector | QS |
| High voltage fuse | FU |
| Earthing switch | QSN |
| Power transformer | T |
| **Voltage transformer cell** | |
| Bus disconnector | QS |
| High voltage fuse | FU |
| Surge arrester | FV |
| Voltage transformer | TV |
| **Intersection circuit breaker cell** | |
| Bus disconnector of the 1st busbar section (with one earthing switch) | QS1 |
| Circuit breaker | Q |
| Current transformer | TA |
| Bus disconnector of the 2nd busbar section (with two earthing switches) | QS2 |

Electrical schemes of power circuits for each of mentioned cell types are shown at Fig. 1 and corresponding list of equipment is given in Table 1 and Fig. 1. Distribution transformer substation as a rule has one busbar divided into two sections. Let us accept this scheme for model DTS. For every section, it is necessary to have one input cell, one voltage transformer cell and one power transformer cell for consumers 0.4 kV power supply. Intersection circuit breaker will be connected according to scheme (Fig. 1b). A number of outgoing transmission lines in real DTS may be large (up to 20-30). However, considering of numerous lines is not needed for the purposes of underlying processes simulation in DTS. The minimal number of lines at one section from the point of view of research is determined with simulation of zero sequence current distribution during earth fault (particularly, for earth fault protection algorithm that uses total zero sequence current). For zero sequence current comparison in different lines and determination of maximum current value, at least three lines should be considered. The larger amount of lines provides no new results and at the same time leads to model size and computing resources increasing, that is undesirable. For this reason, we assume three outgoing line cells for every section in model DTS.

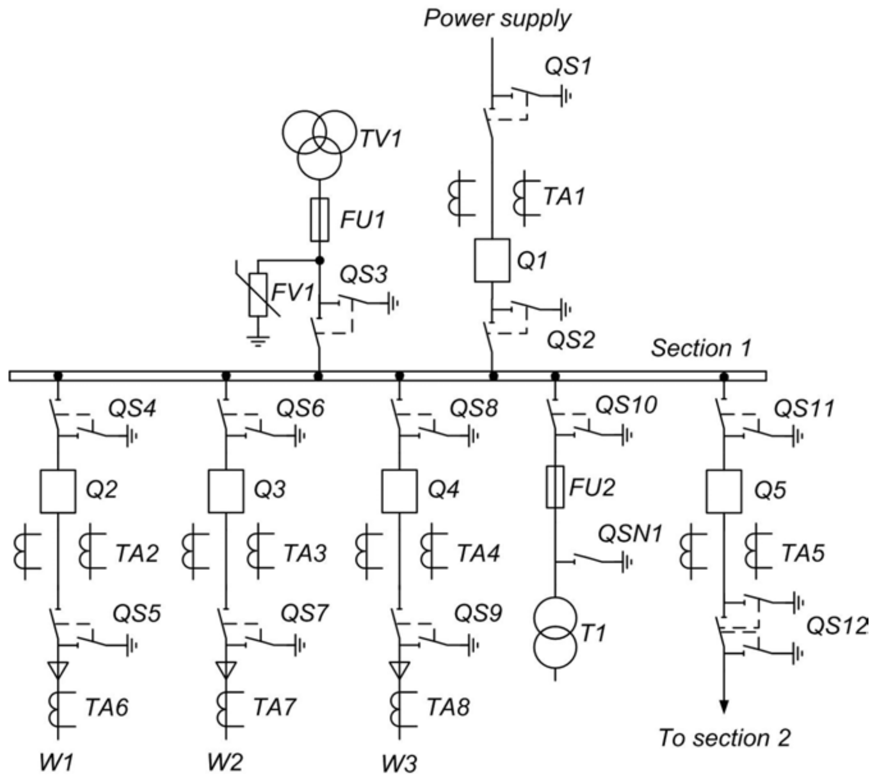


Fig. 2: Electrical scheme of model DTS

An electrical scheme of model DTS, composed with account of conclusions given above is shown at Fig. 2 (first section and intersection circuit breaker cell are displayed; second section equipment is similar to the first section one). In accordance to electrical scheme of model DTS in Simulink graphical editor model scheme was composed using library blocks. For better readability of the scheme, all the equipment for every DTS cell type was merged into a subsystem that has in common case several power and data inputs and outputs. These five subsystems (input, outgoing line, power transformer, voltage transformer, intersection circuit breaker) are the library blocks with higher level than origin Simulink and SimPowerSystems blocks. Using this blocks DTS model can be built with various number of any cell types, so this approach is very convenient. Another advantage is that equipment in the cell is available for viewing, parameters edition and even for change of some origin library blocks.

At Fig. 3, a part of Simulink distribution substation model is demonstrated which corresponds to first busbar section of substation. As an example, let's consider connection of subsystem "VV1" that incorporates equipment of first busbar section input cell. It has power phase inputs "A in", "B in", "C in" that are connected to power supply GS1, power phase outputs "A out", "B out", "C out" that are connected to busbar section, control input "Q Command" for distant closing and opening of input cell circuit breaker and data output "TA Out" by which measurement results (output signals of phase current transformers) are transferred. Similar construction is used for outgoing lines cells subsystems "Line 1" "Line 3" that have phase current transformers and zero sequence current transformers, so in subsystem output two channels for data transferring are present "TA Out" and "TA 3I0 Out", respectively. In power transformer cell "Trans1" there is no high voltage circuit breakers and current transformers, so corresponding subsystem has only power phase inputs and outputs, with 0.4 kV load connected to last. Voltage transformer cell subsystem "TV1" has one data output "TV Out" by which measurement results (output signals of voltage transformer second winding) are transferred.

DTS busbars are represented as connection lines between cell subsystems. This simplified representation is permissible in protection research and allows simulating any kind of damage on busbar by additional resistors connection between phases and earth. Data outputs of subsystems are joined with Simulink blocks "From" and "Goto" into common system. High voltage transmission lines "Line 1-3" and corresponding loads

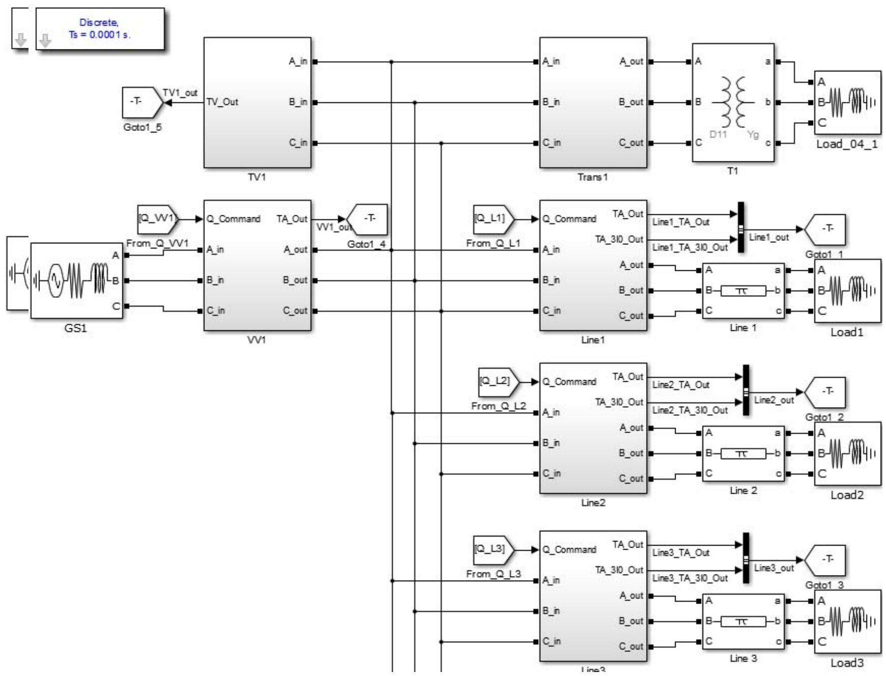


Fig. 3: A part of DTS mathematical model in Simulink (section 1)

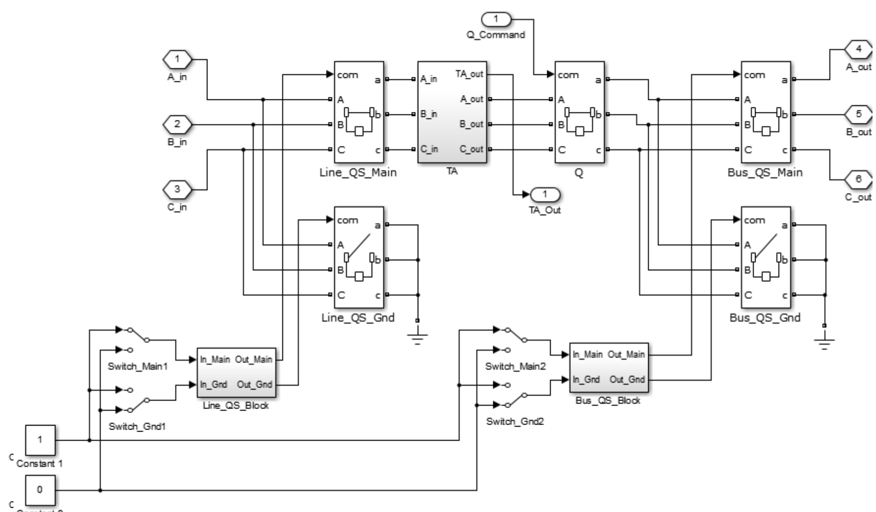


Fig. 4: DTS input cell subsystem in Simulink

"Load 1-3" are not parts of DTS itself but they must be included into mathematical model for operation modes researching.

Let us consider inner structure of input cell subsystem (Fig. 4). A library block SimPowerSystems "Three-Phase Breaker" is taken as a base for power circuit breaker which can be controlled via input "com". Inside the block, values of resistance in closed state and RC snubber parameters connected in parallel with power contacts can be specified as well as initial state of circuit breaker at the simulation start. Since, SimPowerSystems library has no specific model for disconnector, main blades and earthing switches of disconnectors are represented with the same block "Three-Phase Breaker" (at Fig. 4 "Line QS Main" and "Line QS Gnd" main blades and earthing switches of line disconnector, respectively "Bus QS Main" and "Bus QS Gnd" main blades and earthing switches of bus disconnector, respectively).

Unlike circuit breaker Q which can be closed and opened with relay protection command as well as manually, disconnectors in the DTS model can be closed and opened only manually that is completely corresponds to real equipment operation. For this purpose, manual switches "Switch_Main" for main blades and "Switch_Gnd" for earthing switches are provided (block "Manual Switch" from Simulink library), index 1 is used for line disconnector, index 2 for bus disconnector. Toggling them into top position cause closing of corresponding equipment contacts, into bottom position opening.

In the model, a special blocking is included that prevent earthing switches closing when main blades are closed and main blades closing when earthing switches are not opened. At Fig. 4 scheme, this blocking is denoted as "Line QS Block" for line disconnector and "Bus QS Block" for bus disconnector. Blocking is realized as second-level subsystem and uses logic elements from Simulink library.

The model can be equipped with more complex kinds of blocking, particularly between circuit breaker and disconnectors inside one cell (this blocking prevent line and bus disconnector closing and opening when circuit breaker is closed). To achieve this goal, into subsystem with circuit breaker Q additional blocks are inserted that realize triggering logic of circuit breaker secondary contacts and additional data output for connection to common DTS control system. When low-level voltage appears at "com" input, block "Three-Phase Breaker" is opened and blocks are produced low-level voltage at additional data output. Sending high-level voltage signal to "com" input leads to circuit breaker closing, so additional blocks are produced high-level voltage at output. Hence, binary signal at subsystem data output will reflect current stage of apparatus.

Since, secondary contacts of circuit breakers are widely used in relay protection and automatic schemes, they must be represented for proper investigations in DTS model as specified above.

In proposed model, disconnectors are realized in the same way as circuit breakers with library block "Three-Phase Breaker', so we can use described above approach to determine current stage of disconnectors. In this case, additional Simulink blocks represents block-contacts KCA which are used in disconnector's drives for transferring data about stage into signalization and blocking circuits.

A combination of circuit breakers and disconnectors secondary contacts, realized in this way, allows providing in the model circuits for current stage controlling, sufficient for relay protection and automatic as well as for algorithms of centralized relay protection, automatic and control system. Current transformers subsystem (TA at Fig. 4) is based on standard Current Measurement blocks from SimPowerSystems library. In cells 6-10 kV as a rule, current transformers are installed only in two phases (A and C) that is enough for load current measurement, power consumption metering and overcurrent relay protection. Earth faults are detected via separate zero sequence current transformers installed on outgoing cable lines. However, in input cells 6-10 kV and in 35 kV cells there are current transformers in all phases. For this reason, two blocks TA were prepared for mathematical model, that have current measurement in two and three phases respectively, to allow user to compose model scheme for any kind of switchyard.

Zero sequence current transformer model, used in outgoing line cells is also built on current measurement blocks. Zero sequence current $I_0$ is determined at the base of measured phase current values $I_A$-$I_C$ by well-known formula from symmetrical components method (Kulikov, 2003):

$$I_0 = \frac{1}{3}\left(I_A+I_B+I_c\right)$$

Phase voltage measurement at DTS busbar sections is performed with voltage measurement blocks from SimPowerSystems library. A set of voltage measurement blocks allows to determine values of all line-to-line and phase voltages at given section and show them on the screen. Possibilities of current measurement and voltage measurement blocks combined with signal level transformation blocks and mathematical processing blocks are sufficient for DTS operation modes analysis and relay protection testing. When more complex processes must be taken into account, like caused by non-linearity of current transformer magnetizing characteristic, more complex and accurate models of current transformer should be used (Lebedev and Filatov, 2011). A set of current and voltage measurement circuits in combination with described above circuit breakers and disconnectors control circuits allows to build common DTS measurement, signalization and control system with high level of detail. This common system can provide complete verification of all the relay protection, automatic and control algorithms of centralized system with proposed mathematical model using.

After building DTS model in Simulink and parameter settings, a different operation modes and commutations modelling was performed. Particularly, next modes and commutations were investigated:

- Normal operation condition, when all the DTS circuit breakers except intersection circuit breaker are closed and loads are connected to the transmission lines
- Two-phase and three-phase short-circuit in two points: at the end of transmission line and at DTS busbar section
- Closing/opening circuit breakers of outgoing lines and input cells
- Closing/opening disconnectors and blocking scheme testing

## RESULTS AND DISCUSSION

For these investigations in DTS model shown at Fig. 3 additional measurement devices are connected (block scope) for phase currents, phase voltages and control signals visualization. As an example, at Fig. 5 control signal of transmission line "Line 1" circuit breaker (upper diagram) and phase currents of this line (lower diagram) are shown. From Fig. 5, it is clear that at low-level control signal circuit breaker is opened and phase currents equal to zero. When at the moment t = 0.1 sec after simulation start control signal reaches high level, circuit breaker becomes closed and phase current rise to normal value that depends on transmission line impedance and power of connected load. It should be noted that real high voltage circuit breakers have specific value of closing time (time interval from sending command to contact closing) and opening time (time interval from sending command to opening contacts; value of total opening time also contains duration of arc extinction). For example, typical opening time for 6-10 kV vacuum circuit breakers is 0.05 sec. Circuit breaker model realized in Simulink has not such parameter as closing/opening time: switching of circuit breaker occurs immediately after control signal change at "com" input. For non-zero closing and opening time values, that reflect electromagnetic and mechanical inertia of real circuit breakers, it is necessary to add time delay blocks into DTS model (library block time delay).

At Fig. 6 control signal diagrams are presented for main blades and earthing switches of line disconnector in DTS cell and also for signals at the blocking scheme inputs. This figure illustrates performance of blocking between main blades and earthing switches. At the simulation start (t = 0) command to main blades closing has high level and command to earthing switches closing has low level. At the output of blocking scheme, these signals became control signals of main blades and earthing switches, respectively with the same values. Presence of high level control signal cause closing of corresponding apparatus and presence of low

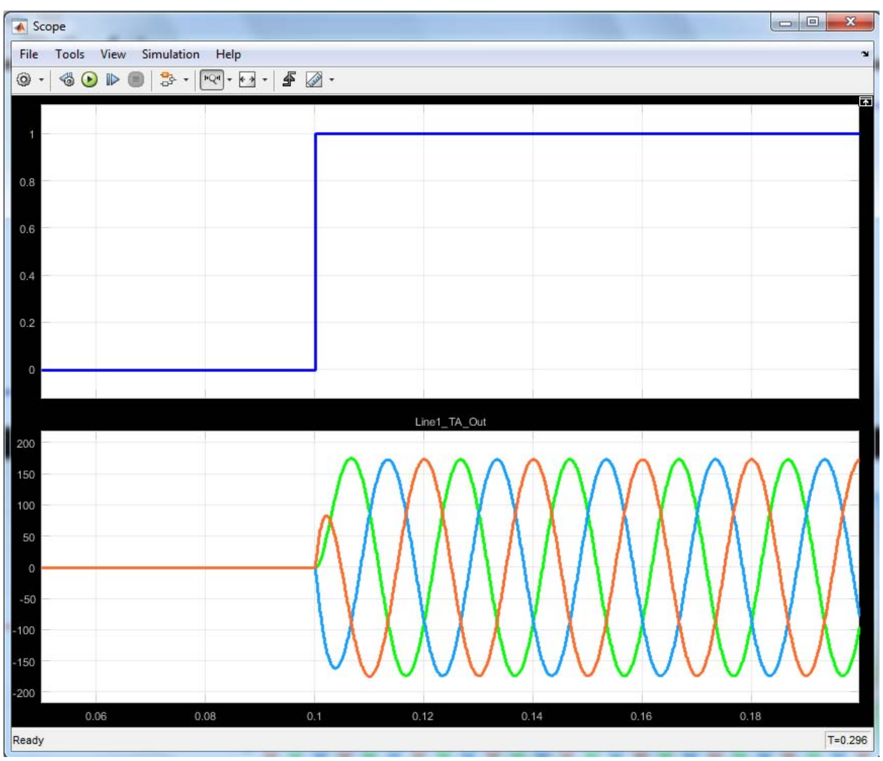


Fig. 5: Transmission line "Line 1" circuit breaker control signal and phase currents

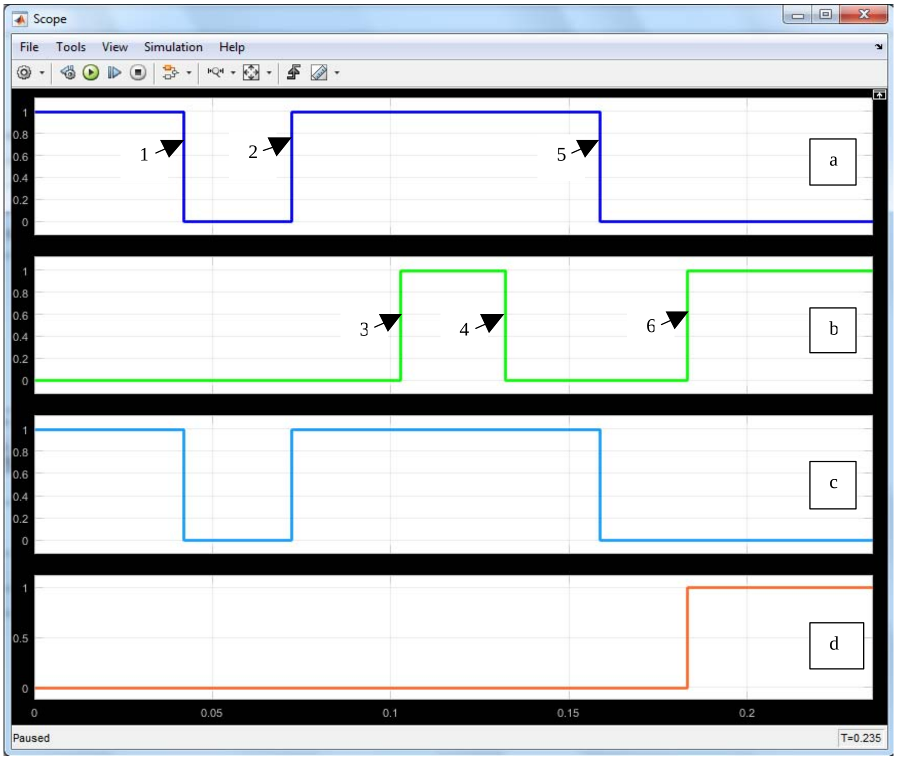


Fig. 6: Signal diagrams in blocking scheme: a) command to main blades closing; b) command to earthing switches closing; c) control signal of main blades and d) control signal of earthing switches

level control signal leads to opening one. Therefore, this combination of control signals means that main blades of disconnector are closed and earthing switches are opened.

Toggling command to main blades closing to low level (equals opening command) is depicted as event 1 at Fig. 6a. Since, main blades opening when earthing switches are opened is permissible, blocking scheme allows generating low-level control signal of main blades and this apparatus becomes opened (diagram "c"). Reclosing of main blades (event 2 at Fig. 6) is also allowed, so toggling blocking input signal to high level leads to generating high-level control signal of main blades and these blades become closed now let's consider attempt to send command to earthing switches closing (event 3 at Fig. 6). Control signal of main blades ("c" at Fig. 6) has high level, so main blades are closed. In this situation, earthing switches closing is prohibited that's why blocking scheme don't pass command to earthing switches closing, keeping low level control signal of earthing switches and their opened stage. Return of command to earthing switches closing to low level (event 4) cause no changes.

However, when firstly main blades are opened (event 5 at Fig. 6a) and then command to earthing switches closing is toggled to high level (event 6 at Fig. 6b), this command will be passed to blocking scheme output and will generate high level of earthing switches control signal (Fig. 6d). Earthing switches closes because this operation is already permissible. Hence, diagrams at Fig. 6 confirms correct operation of blocking between main blades and earthing switches of disconnectors in DTS model.

## CONCLUSION

For the five typical DTS cells (input cell, outgoing line cell, voltage transformer cell, intersection circuit breaker cell, power transformer cell) electrical schemes of power circuits and list of equipment are presented. At this base, electrical scheme of model distribution transformer substation was prepared and Simulink model was composed using Simulink and SimPowerSystems library blocks. Equipment of the cells is joined into subsystems with power and data inputs and outputs, that allows to build DTS model with various number of any cell types. Disconnector model with main blades and earthing switches based on library block "Three-Phase Breaker" is proposed. DTS model provides secondary contacts of circuit breakers and disconnectors, current and voltage measurement circuits, circuit breaker control circuits. This provides an opportunity to build common relay protection, automatic, measurement and control system of DTS with high-level details as well as to realize complete verification of all the relay protection, automatic and control algorithms of centralized system with proposed mathematical model using. Operation modes and commutations modelling is performed, correct operation of blocking between main blades and earthing switches of disconnectors in DTS model is demonstrated.

## ACKNOWLEDGEMENTS

This research was financially supported by the Russian Federation Ministry of Education and Science within the federal target program implementation “Research and development on priority trends of scientific-technological complex of Russia development during 2014 - 2020”, grant provision agreement No. 14.577 .21.0194 issued on 27/10/2015 - stage 2, a unique identifier for applied scientific research (of a project) RFMEFI57715X0194.

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