DESIGN AND TEST OF SIMULATION MODEL OF THE CONTROLLER OF ELECTROMECHANICAL TAP-CHANGERS FOR HV/MV TRANSFORMER

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Abstract: At present, the simulation model of the electromechanical tap changer controller is not generally available. It is necessary in order to carry out tests of the voltage regulation system in the Main Supply Point (MSP). It is a lower voltage regulation system. The article presents simulation models of the tap changer controller working in a HV/MV station. The construction of all subsystems of the model is presented. Various methods of implementation of current compensation were also considered. The subsystems of the model and the whole have been simulated.

Keywords: Simulink, the regulator tap-changers for HV/MV transformer, the simulation model.

1. INTRODUCTION

The problem of voltage regulation in electric power grids is described in many publications and documents, including [Ustawa z 10 kwietnia 1997; Faiz and Siahkolah 2006, 2011; Machowski 2007; Rozporządzenie Ministra Gospodarki z 4 maja 2007; Szczerba 2007; Wiszniewski 2007; Faiz and Javidnia 2008; Machowski, Bialek and Bumby 2008; Kot and Szpyra 2009; PN-EN 50160:2010; Brusiłowicz, Rebizant and Szafran 2011; Gao and Redfern 2011; Brusiłowicz and Szafran 2012, 2013, 2014b; Lis 2013; Cieślik 2014; Ram et al., 2014; Chen and Jonsson 2015; Pawlicki 2015; Korpikiewicz and Mysiak 2017b]. This is complex problem: voltage stability, quality of voltage regulation, application of electromechanical or semiconductor tap changers, control algorithms in regulators, design of voltage governor, application fuzzy control in voltage governor, control quality indicators, legal and technical requirements, methods for measuring the parameters of the power grid, electric power quality, current compensation. The

purpose of this article is to create and verify a simulation model of the tap changer controller for the HV/MV transformer installed in the Main Supply Point (MSP).

This model has been developed in the universal Matlab/Simulink environment. This model is used to study the influence of the tap-changer controller algorithm on the quality of voltage regulation. The controller of this type works in the on the lower side of transformer regulation mode. High power transformers used in power systems (block, coupling, reduction) equipped with On Load Tap-Changer (OLTC) load are called regulating transformers [Jezierski and Hasterman 1983, p. 415; Machowski 2007, p. 136]. The 110 kV/MV regulating transformer is supplied with a voltage with a variable run time. Moreover, in the MV/LV stations supplied from the considered MSP, the demand for active and reactive power changes over time.

The voltage characteristics at these MV/LV substations also change depending on the composition of the currently active electric energy consumers, their load level. The presented factors affect the quality of voltage regulation in the MV and LV networks. For these reasons, the developed model is part of the entire voltage regulation system. The remaining elements will be a replacement power system model by equivalent – Thevenin system. Regulating transformer supply a variable value of voltage in time depending on active and reactive power flow in the HV and LV power systems. The next element of the system will be the HV/MV transformer model together with the on-load tap changer (OLTC).

The last element is the model of the MV power network together with substitute loads (variables at load time – active and reactive powers in MV/LV substations). There is a Simulink toolbox (Simscape Power System) that facilitates simulation of the power network elements [The MathWorks 2017, 2018a]. However, the tap changer controller model has a characteristic independent of the error (constant delay mode) – Three-Phase OLTCRegulating Transformer (Phasor Type). The tap-changers controller model is integrated with a transformer model. Modifying existing components of this toolbox is difficult. This fact hinders the synthesis of a new type of regulator with the use of this toolbox.

Power-electronic devices in power system are increasingly used. Therefore, the influence of the use of the electronics tap-changer with the controller implementing the classic algorithm [Korpikiewicz 2017; Korpikiewicz and Mysiak 2017a] was examined. A significant influence of the OLTC type on the quality of voltage regulation has been demonstrated.

Many publications use a very simplified model of a controller, the control transformer or a tap-changer, among others: [Joon-Ho and Jae-Chul 2000; Choi 2001, Joon-Ho Choi and Seung-Il Moon 2009; Brusiłowicz, Rebizant and Szafran 2011; Brusiłowicz and Szafran 2012, 2014a; The MathWorks 2017]. However, in order to examine the quality of voltage regulation, it is required to map the non-linearity as well as the dynamic properties of the controller. The simple mathematical description of the controller is contained in [Joon-Ho Choi and Seung-Il Moon 2009]. A generalized model of the tap-changer controller is shown

in the book [Zajczyk 2003]. In [Zajczyk 2003] an acceptable transformer work area is shown (1). It is realized by locks and protection units.

$$\begin{cases} U_{TG\min} \leq U_{TG} \leq U_{TG\max} \\ U_{TD\min} \leq U_{TD} \leq U_{TD\max} \\ I_{TG} \leq I_{TG\max} \\ I_{TD} \leq I_{TD\max} \end{cases} \tag{1}$$

where:

U_{TGmin}, U_{TGmax}, U_{TG} – minimum, maximum and measurement voltage on the upper side of transformer,

U_{TDmin}, U_{TDmax}, U_{TD} – minimum, maximum and measurement voltage on the lower side of transformer,

I_{TG}, I_{TD} – measuring current of the upper and lower side of transformer,

I_{TGmax}, I_{TDmax} – maximum current of the upper and lower side of transformer.

The adjustable variable is the voltage on the lower side of the transformer U_{TD}. The control signals are the binary signal "change tap up" and the binary signal "change tap down". The current measurement serves to protect the tap-changer against switching operations when overloaded, which can shorten its service life. There are disturbances on the control system changes in active and reactive power demand, change of network configuration, change of the effective value of transformer supply voltage. Traditional on-load tap-changers have limited switching operations. The lower voltage regulation system is presented in Fig. 1.
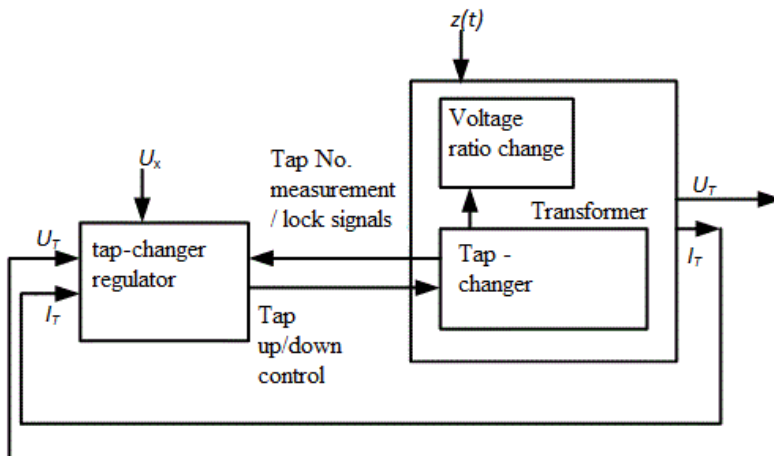

Fig. 1. Lower voltage control system using transformer tap-changer; U_x – voltage setpoint; U_T and I_T – voltage and current on the selected transformer side; z(t) – disturbance of the control system

The simulation model developed is to meet the following requirements:

- Versatility. Thanks to the use of the classic Simulink model it is possible to modify, extend or change the control algorithm.
- In classic Simulink model we can build new specific block used e.g. S-function [The MathWorks 2018b,c].
- The subsystems of the model should correspond to the division into actual devices, i.e. a separate controller model, a separate HV/MV transformer model and a separate tap-changer model. This allows to examine the impact of the control algorithm of the selected device on the operation of the entire system.
- The input and output signals correspond to the actual input or output signals of the URT[1] controller or settings relevant to the control algorithm [Kołodziej and Jamielity 2012].
- Implementation of regulation algorithms for the version with several transformers has been abandoned.
- It has been assumed that the actual number of the tap is available.

The description of the regulation by tap-changers in power substations is described, among others [Zajczyk 2003; Machowski 2007]. A detailed control algorithm is included in the technical documentation of the tap changer controller developed at the Institute of Power Engineering [Kołodziej and Jamielity 2012]. Current compensation is described in, among others [Hellman and Szczerba 1978; Szczeciński and Zajczyk 2010; Sobczak and Rink 2013]. The implementation of current compensation has been abandoned because in practice it is switched off. This is due to the problematic selection of compesation impedance [Czapla and Jemielity 2010; Czapla and Ogryczak 2012]. This problem requires further research, which will affect the regulator's measuring system and the final simulation model. The model uses a delay characteristic depending on the error, because this mode of the controller is selected the most often. In this mode, at larger errors, the regulator changes the tap after a shorter period of time. This mode provides better voltage regulation quality.

The controller of OLTC has relay control elements. This is due to the fact that the control signal is discrete (tap down, work on the current tap, tap up) and the change of the tap changes the lower voltage in a stepwise (discreetly) manner. The measuring unit of the controller after determining the voltage deviation (voltage error) (see dependence 1) uses the static characteristics of the three-position relay with the dead zone = 2 · delta_U and hysteresis e (see Fig. 2). The relay output signal w has the meaning described in Table 1. The hysteresis e prevents cyclic changes in the state w when the voltage error ε changes near any dead zone threshold.

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[1] URT – controller of tap-changers HV/MV transformer developed in Institute of Power Engineering Gdańsk Division.

Table 1. Output signal of the three-position relay w

w	Signification	Description
+1	Error above upper dead zone threshold	Measuring time to change the tap "up" in order to increase the lower voltage
0	Error in dead zone	Work on the actual/current tap number. If time measurement has been started then counting to the "other side", i.e. increasing the time to change the tap
−1	Error below the lower threshold of the dead zone	Measuring time to change the tap "down" in order to decrease the lower voltage
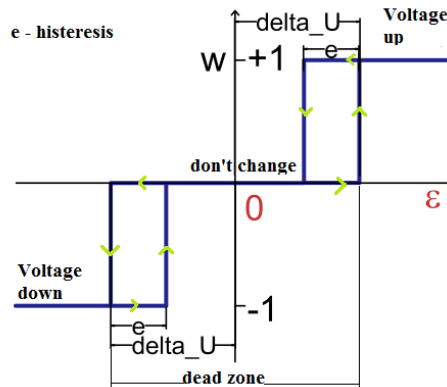
Fig. 2. Static characteristics of three-position relay with dead zone – 2 · delta_U and hysteresis – e

$$\varepsilon = U_x - U_T \qquad (2)$$

where:

U_x – voltage setpoint,
U_T – voltage on the lower voltage side.

   If the signal $w \neq 0$, i.e. the measured voltage is outside the dead zone, the tap will change up or down depending on the sign of the error (signal w) after the specified delay has elapsed. This prevents tap-changes caused by temporary voltage changes. The total number of switching operations is limited by the persistence of the OLTC. This delay is counted down from the initial value to zero. If the signal w changes to 0, the calculated delay time "goes back" – it counts up to the initial value. The timing of the delay dependent on the voltage error is called the integral criterion. This criterion is described by discreetly relationships (2) and (3). Control using digital devices takes place at discrete times.

$$A_1(t+1) = \begin{cases} A_1(0) = initial \\ A_1(t) - |\varepsilon(t)|, w(t) = 1, A_1(t) \geq |\varepsilon(t)| \\ 0, w(t) = 1, A_1(t) > 0, A_1(t) < |\varepsilon(t)| \\ A_1(t) + const, w(t) = 0, A_1(t) \leq initial - const \end{cases}$$ (3)

$$A_2(t+1) = \begin{cases} A_2(0) = initial \\ A_2(t) - |\varepsilon(t)|, w(t) = -1, A_2(t) \geq |\varepsilon(t)| \\ 0, w(t) = -1, A_2(t) > 0, A_2(t) < |\varepsilon(t)| \\ A_2(t) + const, w(t) = 0, A_2(t) \leq initial - const \end{cases}$$ (4)

where:

initial   – initial value,
A_1 – measured value of the positive error integral,
A_2 – measured value of the negative error integral,
$A_1(0)$ – initial value of positive error integral,
$A_1(t)$ – value positive error integral at t - time,
$A_1(t+1)$ – value positive error integral next time,
$A_2(0)$, $A_2(t)$, $A_2(t+1)$ – have the analogous meaning as A_1,
const   – constant number used in integrator when $w = 0$ (calculated delay time "goes back").

Next block are locks that prevent changing the tap due to, among others obtaining an extreme tap in a given direction, overloading the tap-changer, lowering the voltage below the setting of the undervoltage blockade or increasing the voltage above the overvoltage blockade setting. The interlocks take into account the direction of the tap changes, in addition to overload and undervoltage (see Table 2). The undervoltage blocking is implemented in both directions due to the risk of loss of voltage stability.

Table 2. List of controller locks [Kołodziej and Jamielity 2012]

The name of the lock	Lock type
Overvoltage U>	Changing the tap in the direction of increasing the lower voltage
Undervoltage U<	Tap changes in both directions
Overload S>	Tap changes in both directions
From the topmost position of the tap Z>	Increase the number of the tap
From the extreme bottom position of the tap Z<	Lowering the tap number

After fulfilling the integration criterion and if the blocking system permits this, the controller activates the relay "control above the switch", when $w = 1$ or the relay "lower control of the switch", when $w = -1$. The controller turns off the relay when [Kołodziej and Jamielity 2012]:

- a change in the intended number of the tap is detected;
- the maximum time has been exceeded to change the tap.

2. SIMULATION MODEL OF CONTROLLER FOR TAP-CHANGERS

2.1. Block diagram of the HV / MV transformer tap-changer controller

The principle of operation of the OLTC regulator is presented in [Hellman and Szczerba 1978; Machowski, Bialek and Bumby 2008; Kołodziej and Jamielity 2012]. In order to explain the principle of operation of the regulator, its block diagram and signal flow between blocks are presented in Fig. 3.
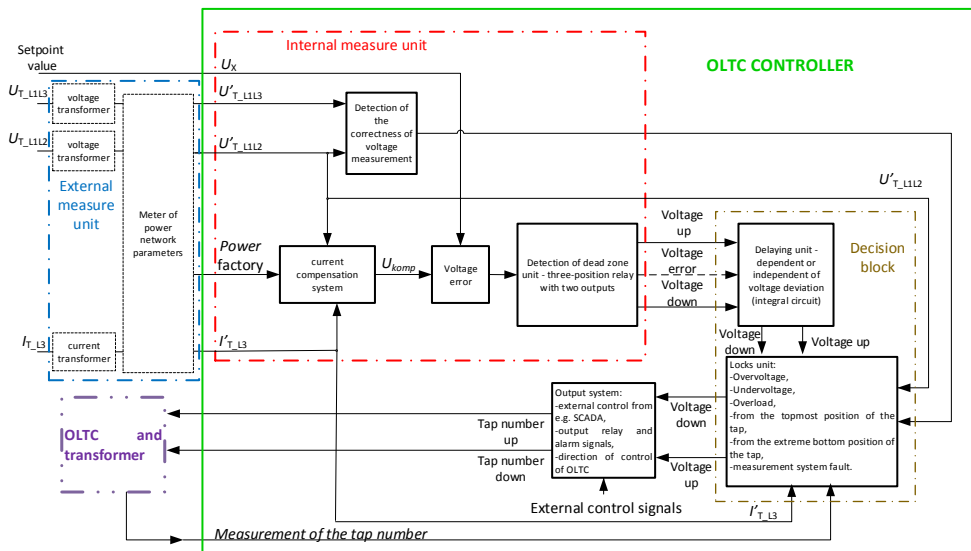

Fig. 3. Block diagram of the HV/MV transformer tap-changer controller

The external measuring part has been marked with a blue dotted line. The main function of this element are indirect measurements of alternating voltage and current as well as power network parameters. It can provide measurement signals via a communication link (e.g. RS 485). The internal measuring part has been marked with a red dotted line. The purpose of this system is to determine the voltage error including current compensation. In addition, the voltage error is compared to the dead zone. The decision block generates control signals for the tap-changer. Due to the limited number of switching operations of the tap-changer, the tap-changer control signals are not generated based on the instantaneous voltage error. The regulator should react to the voltage error outside the dead zone lasting a certain time. They are generated based on the integral voltage error, when $w = 1$ or $w = -1$. The hysteresis e, delay unit and dead zone prevents unecessary switching of OLTC. Also switching frequency is lower. Siutable selection of dead zone width,

time characteristics of the delay block and hysteresis width ensures stable operation of the OLTC. The decision block takes into account the signals of all controller locks.

The output system is made of output relays. It includes active external control signals and direct control of OLTC.

Table 3 presents the parameters of the tap-changer controller which determines its operation. The model fails to check the correctness of the settings entered by the user. The communication via digital link has not been modeled, because these are functionalities that do not affect the controller's operation in the low voltage control mode.

Table 3. Parameters of the tap-changer controller

Symbol	Description	Value	Unit
delta_U	Half of the width of the dead zone (see Figure 2)	350	V
e	Hysteresis (see Fig. 2)	20	V
S_n	Rated power of the transformer	26	MVA
loock S>	Setting of the overload lock	50	% Sn
Liczba_Z	Number of tap-changers	27	-
U_n	Rated voltage	15 000	V
U_x	Voltage setpoint	15 500	V
Blokada_U<	The level of activation of the undervoltage block	80	% Un
Blokada_U>	Level of overvoltage block activation	120	% Un
	Regulation type. Specifies whether the delay time of the change of the hitch depends on the voltage deviation	depending on the voltage error	-
	Control direction of the tap changer, i.e. Z+, U+ or Z-,U+.	Z+U-	-
const	Constant responsible for the countdown speed	20	-
initial	The initial value from which the delay time is measured	500 000	-
Ulimit	Limit value of the positive error above which the tap-changer without delay	3500	V

The first element of the regulator is the internal measuring unit shown in Fig. 3. The regulator has two binary outputs corresponding to "change tapnumber up" and "change tap number down". For this reason, two binary outputs have been created from one tristate output.

2.2. The concept of an external measurement system

Currently, single-phase measurements are used, assuming the symmetry of a three-phase circuit. In order to implement the measurement system, it is possible to use the power network parameter meter with a digital interface, eg N27P from Lumel with RS 485 and Modbus RTU Slave protocol. Intermediate and medium voltage current transformers (CTS 12 from KPB Intra Polska) and voltage transformers (VTS 12 from KPB Intra Polska) are required for intermediate measurements (15 kV network).

In order to perform test voltage measurement, an additional voltage transformer and an AC voltage converter should also be used with RS 485 and Modbus RTU protocol. However, the system with one three-phase power network parameter meter with RS 485 will be cheaper than the single-phase network parameter meter, AC voltage converter and standard signal converter on RS 485. For this reason, the parameter meter for the three-phase network N14-11000 was selected (Lumel).

The schematic of the external measurement system is presented in Fig 4. This part will be modeled and presented in the next publication.
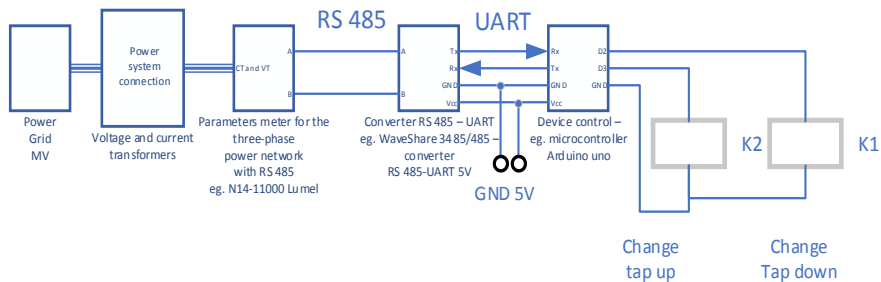

Fig. 4. Schematic diagram of the external measuring system of the tap-changer controller

2.3. Construction of a simulation model of the internal measurement system

The Simulink library was created with the classic tap changer controller model. The controller's sub-system is shown in Fig. 5. Definitions of input and output signals are presented in Table 4. The model was created from many subsystems. The most important of them are presented in Fig. 6.
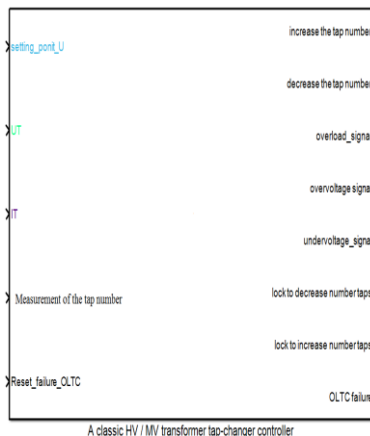

Fig. 5. The subsystem of the tap-changer controller

Table 4. Parameters of the tap-changer controller

| Lp.	Symbol	Description
		INPUTS
1	U_T	The rms (Root Mean Square) value of phase-to-phase voltage measured on the MV side - regulated variable. The regulators usually use two measuring systems (basic and control). If the difference between the two systems exceeds the set threshold, an alarm is generated.
2	I_T	The rms value of the current of the selected phase measured indirectly (through the current transformer).
3	U_k	The setpoint of value of phase-to-phase voltage on the MV side.
4	Measurement of the tap number	Analog value corresponding to the current tap number. In the real system, depending on the method of measuring the tap number, there are a number of binary inputs. On some circuits, only the drive confirmation signal may be available.
5	Reset_failure_OLTC	The signal canceling the alarm caused by the lack of reaction of the tap changer at a given time on the tap change signal.
		OUTPUTS
1	increase tap number	Controller output - binary signal for tap changer - increase the tap number.
2	decrease tap number	Controller output - binary signal for tap changer - decrease the tap number.
3	overload_signal	Signaling of the overload OLTC
4	overvoltage_signal	Signaling of overvoltage blocking
5	undervoltage_signal	Signaling of undervoltage blocking
6	lock to decrease number taps	Lockout change signaling in the direction of reducing the tap number
7	lock to increase number taps	Lockout change signaling in the direction of increasing the tap number
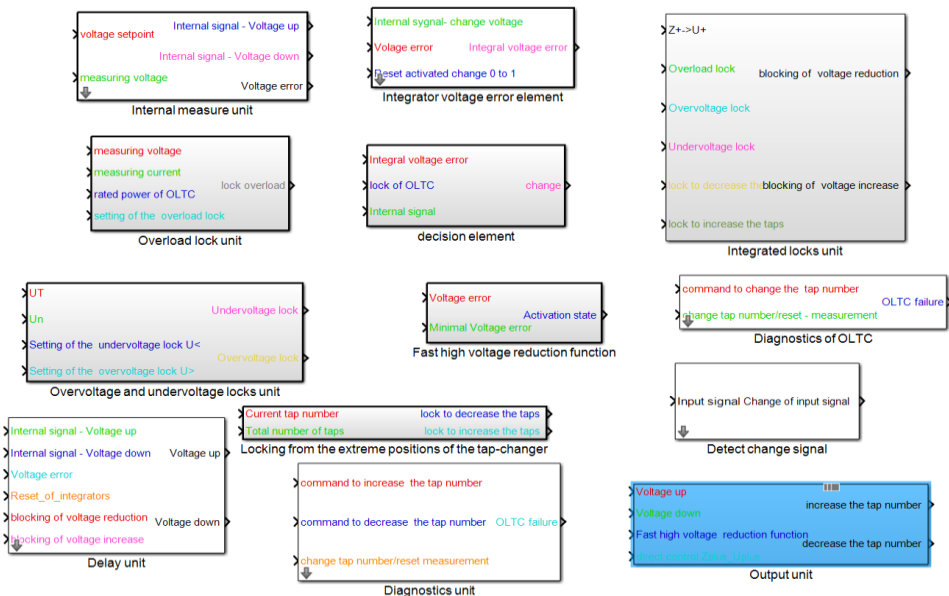
Fig. 6. Main subsystems of the tap-changer controller

After resignation from the implementation of current compensation, the internal measuring system is reduced to a three-state relay with dead zone and hysteresis. The schematic of the simulation model is presented in Fig. 7.
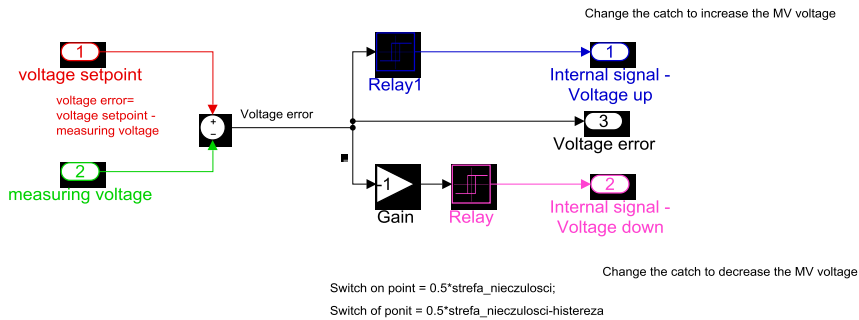
Fig. 7. Construction of the internal measuring system

2.4. Testing the simulation model of the internal measurement system

Fig. 8 shows the simulink model used to test the internal measuring system of the controller model. The test consisted in creating a trapezoidal measuring voltage using three Ramp blocks and performing simulations at a fixed setpoint. Vectors of output variables (Up, Down, Verror) and input variables (Vmeasure, time) were saved in the Matlab workspace. Graphs were created based on simulation results.
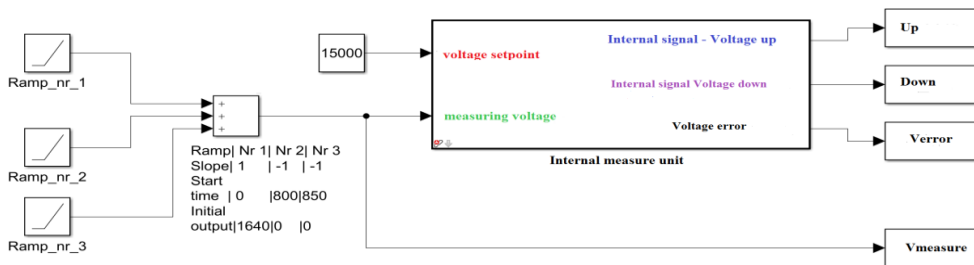
They are presented in Fig. 9 and 10.

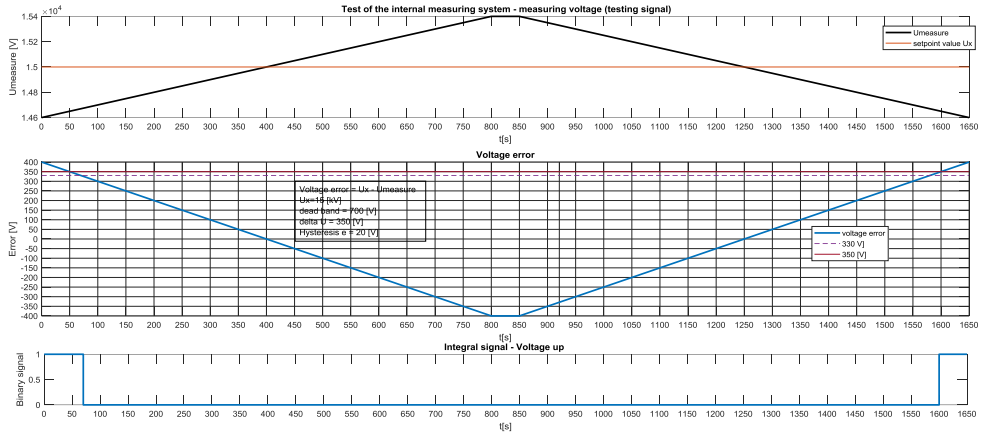**Fig. 8.** Simulation scheme for testing the internal measuring system

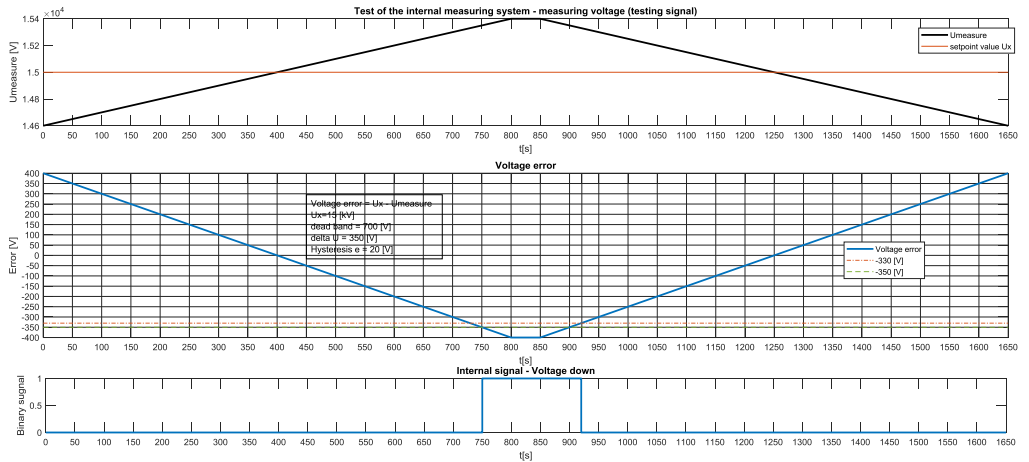**Fig. 9.** The test results of the internal measuring system of the regulator – voltage up signal

Fig. 10. The test results of the internal measuring system of the regulator – voltage up signal

3. IMPLEMENTATION OF THE INTERNAL MEASUREMENT SYSTEM ON THE ARDUINO UNO PLATFORM – CASE STUDY

Due to the use of integrators in other subsystems, a constant control cycle or accurate measurement of them should be provided. In addition, communication through the UART interface with the external measuring system must be ensured. The network parameter meter has an RS 485 interface and Modbus RTU protocol. The meter provides measurement data - works as a slave. Measurement signals must be delivered via a digital link and not via analog inputs. This is due to the large number of parameters supplied and the accuracy of measurements being independent of the analogue inputs of the control device. Serial communication in Arduino Uno uses interrupts. In order to execute functions at exactly equal intervals, interruptions are also used. Arduino Uno is not multitasking system. The multi-tasking platform is Arduino Due. In Arduino Uno, you should not use several mechanisms that use interrupts. If one interruption in Arduino Uno is in progress and subsequent ones occur – they will be ignored. This can cause, for example, erroneous communication. Maintaining a constant cycle time may be difficult due to the variable time of communication with the meter (possible retransmission of frames). The delay function uses interrupts. Thus, it will not work properly when we have UART communication running. However, you can use the delayMicroseconds function. The TimerOne library for determining exact time intervals also uses interrupts. By analogy, the milis () and micros () functions can not be used.

Therefore, the following requirements must be met simultaneously:

- reliable communication via RS 485 and Modbus RTU protocol at 19.2 kbit / s;
- constant control cycle time or accurate measurement of the control cycle time;
- possible implementation of other functions, e.g. handling outputs, keyboards.

The following should be implemented:

- UART interface test when transferring numeric data;
- cooperation test Arduino Uno with UART-RS485 converter;
- test the ability to implement the Modbus RTU master protocol on Arduino Uno. Test of available libraries;
- test of correctness of reading of measured values;
- determining the shortest control cycle time;
- examining the integrator implementation possibilities.

4. MODEL VALIDATION – TIME CHARACTERISTICS TEST

This method consists in performing a series of measurements (simulations) at a fixed value of the tap-changer number by changing the value of the voltage error step by step. The initial size is the change time of the tap-changer.

The obtained characteristic (Fig. 11) confirms the correctness of the dependent characteristic – the greater the voltage error, the shorter the change time of taps.
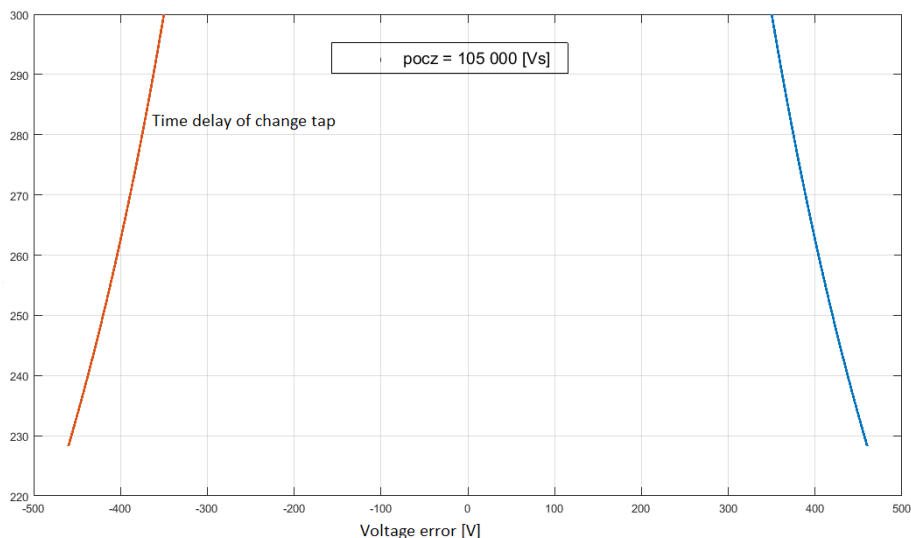
Fig. 11. Timing characteristics of the tap-changer controller depending
on the voltage deviation

5. RESULTS

As a result of the work, a proven model of the regulator was obtained. The possibility of its implementation on the Arduino Uno platform was also examined.

6. CONCLUSIONS

The controllers of electromechanical tap-changers are slow-acting regulators, step by step (sequential change of taps) and discontinuous and non-linear with variable delay. They have a number of interlocks constituting a combination system. These features result from the discrete output signal and operating characteristics of the tap-changer (limited number of connections). Mathematical analysis of the control system requires the use of advanced analysis techniques of dynamic non-linear systems. The construction of a simulation model that takes into account non-linearities and dynamic properties allows the implementation of tests of the low voltage regulation system. Fourteen parameters were identified in the controller model. It is required to develop a model of electromechanical tap changer, HV/MV transformer and power grid. These models should take into account transient phenomena in order to determine the impact of switching commutation phenomena on the quality of voltage regulation. Simplified static models that are insufficient to carry out these tests are widely used.

The created simulation model, despite the simplifying assumptions (work with one transformer, no validation of the introduced settings was modeled, no phenomena of communication between the controller and the master devices was modeled) is a multi-level composite object (18 elements and subsystems). Identification of these parameters is required. The full presentation of the model is not possible in one paper.

Individual subsystems (blocks) were tested, generating sets of input data and analyzing result signals. The entire model created was checked on the basis of time characteristics obtained on the basis of simulation tests. The simulation results confirm the correct operation of the controller model.

A full analysis of the operation of the low voltage regulation system is possible only after the development of the remaining component models and simulation of the entire control system.

In order to examine the possibility of using the selected hardware platform for the construction of the tap changer controller, the following should be implemented:
1. UART interface test when transferring numeric data.
2. Cooperation test Arduino Uno with UART-RS485 converter.
3. Test the ability to implement the Modbus RTU master protocol on Arduino Uno. Test of available libraries.
4. Test of correctness of reading of measured values.
5. Determining the shortest control cycle time.
6. Examining the integrator implementation possibilities.

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