TRANSFORMER'S AUTOMATIC LOCAL VOLTAGE CONTROL IN ELECTRICAL POWER SYSTEMS

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Menținerea tensiunilor în limite admisibile în toate nodurile unui sistem se realizează prin combinarea reglajului centralizat cu cel local. Lucrarea de față are drept scop evidențierea importanței reglajului local prin menținerea tensiunii în limite admisibile într-un nod din sistem cu ajutorul transformatoarelor /autotransformatoarelor echipate cu dispozitiv de reglaj automat al ploturilor. Lucrarea deasemenea propune o soluție de implementare şi parametrizare ale unui dispozitiv de reglaj automat al tensiunii pentru o stație din sistemul electroenergetic național (SEN) în care momentan nu este implementată o astfel de soluție de reglaj şi analizează comportarea acestuia pentru diverse regimuri de funcționare. Calculele au fost realizate într-o stație de interes major 400/220/110 kV din rețeaua de transport a SEN pe un autotransformator de 400/220 kV şi 400 MVA.

In order to maintain in tolerable ranges the voltages of a power system the centralized and the local regulation are combined. The paper is proposing to relieve the importance of the local regulation/control, maintaining in tolerable ranges the voltages in a specified bus of a power system using the power transformers/ autotransformers equipped with an automatic voltage control device. The paper also proposes a solution for implementing and setting an automatic voltage control device for a substation of the national power system, in which is not implemented for the moment this kind of regulating solution, and analyze the its behavior for different operating conditions. The study was made in a very important 400/220/110 kV substation of the transmission network of the Romanian National Power System on a 400/220 kV and 400 MVA autotransformer.

Keywords: automatic voltage control (AVC), on-load tap-changer (OLTC)

1. Introduction

Most network power transformers/autotransformers and large voltage regulators are equipped with manual or automatic on-load tap-changers (OLTC) so that the voltage ratio and hence the secondary voltage may be varied as the load supplied by the transformer changes. Manual control may be used for transformers whose tap positions are changed only infrequently, such as

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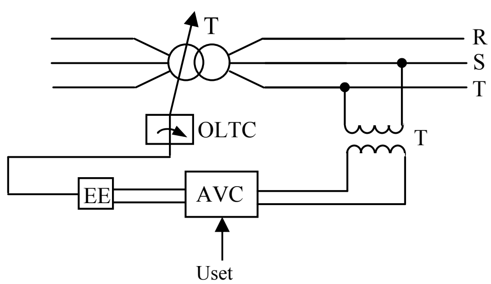
transformers at generating stations. Manual control may be local, at the substation or remote, at a central control centre. Automatic control is provided on transformers in the high-voltage networks. The objectives usually concern some or all of the following:

- Control the voltage at the local substation bus or at some remote load bus
- Control the power factor and VAr flow in the network transformer
- Share load among transformer connected in parallel so as to keep them "in step" to minimize circulating currents [1]

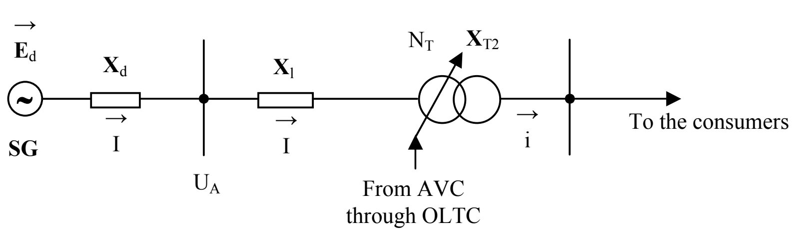
2. Voltage and tap changer controls

The automatic voltage control of the power transformer /autotransformer) is made as a step-by-step principle, using an on-load tap-changer (OLTC) equipped with execution equipment (EE) which is generally a motor-drive mechanisms.

In Fig. 1 is shown the principle method of the automatic voltage control /regulation of the power transformer /autotransformer and the reactance's scheme:



a.



b.

Fig.1. Automatic voltage control of the transformers / autotransformers:
a. Principle scheme; b. scheme

The execution equipment/the motor drive mechanism actuate over the OLTC modifying step-by-step the tap position and hence the voltage ratio $N_T = \frac{U_A}{U_B} = \frac{i}{I}$.

If we consider Fig. 1.b, we can write the equations:

$$\underline{u}_{cons} = \underline{u}_B = \left[\underline{E}_d - j\underline{I}\left(X_d - X_l\right)\right]\cdot\frac{1}{N_T} - j\cdot\underline{i}\cdot X_{T2} \tag{1}$$

$$\underline{u}_B = \frac{\underline{E}_d}{N_T} - j\cdot\underline{i}\cdot\left[\frac{\left(X_d + X_l\right)}{N_T^2} + X_{T2}\right] = E_d^{'} - j\cdot\underline{i}\cdot\sum X \tag{2}$$

$$\Delta N_T \rightarrow \Delta\left(\sum X\right) \rightarrow \Delta u_B \tag{3}$$

The equations 1, 2 and 3 define the principle of the regulation method, showing how the changing of the voltage ratio influence the customer voltage, U_2.

It is obviosly the fact that if N_T is changeing the total reactance $\sum X$ of the system will vary and so, the regulated voltage U_2. The second impact of the AVC, which concerns the modification of $\underline{E}_d$ and $\underline{E}_d^{'}$ make possible to use the voltage regulation in no-load conditions or something very close to this situation [2].

3. Automatic voltage control

The load-side (secondary) voltage of a transformer is subject to cyclic and random fluctuations due to variation of system loads and operating conditions. The objective of automatic voltage control (AVC), also called automatic voltage regulator (AVR), is to control the operation of the on-load tap-changer (OLTC) so as to maintain the secondary voltage close to a set value. The AVC relays determine if the secondary voltage needs to be increased or decreased, and sends a signal to the OLTC control to change taps in the appropriate direction [1], [3].

3.1. Voltage settings

There are two main settings as shown in Fig. 2; these are the voltage setting, V_{SP}, target or band center voltage V_{SP} and the voltage tolerance V_{TOL} or voltage bandwidth $V_B = 2 \times V_{TOL}$. The voltage band remains centered about the voltage setting if it is changed. A timer starts when the voltage strays outside the tolerance band. There is usually a built-in hysteresis V_H and the timer does not drop out unless the voltage strays back inside the inner band $V_{SP} + (V_{TOL} - V_H)$. If the voltage stays outside this inner band until the timer times out a raise or lower signal is sent to the OLTC to reduce the absolute voltage deviation $|V - V_{SP}|$. If the voltage is still outside the outer band, the timer starts again and the whole process is repeated. Another mode of operation, called sequential mode, changes taps continuously without any time delay (except for the initial tap change) until the voltage returns to inside the selected band. The voltage changes by the step voltage V_{STEP}. To avoid the possibility of hunting, the tolerance band must be wide enough so that it is not possible for a single tap step to change the voltage from just outside the inner band on one side to just outside the outer band on the other side because this would then immediately initiate a tap change in the reverse direction [1].

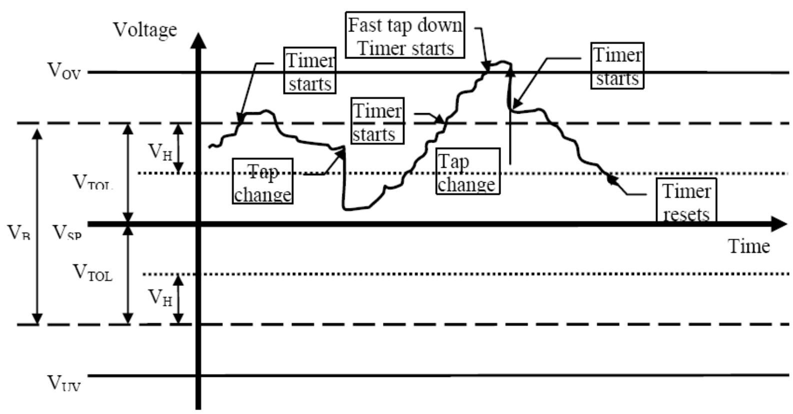


Fig. 2. Automatic Voltage Control

For the case of study presented in this paper was considered the settings in table 1.

Table 1

The setting values of the AVC using OLTC

No.	Variable	Value	M.U.
1	V_{SP}	231.00	kV
2	V_B	2.00	kV
3	V_{TOL}	1.00	kV
4	V_H	0.50	kV

On the other hand too large a value of V_{TOL} could result in excessively large voltage deviations. In practice V_{TOL} is often set equal to V_{STEP}. Other AVC voltage settings include the following:

- Voltage reduction control is provided to enable the set voltage, V_{SP}, to be decreased in emergencies to reduce the load on the system. The tolerance bands remain centered around the new value of V_{SP}. Typically 2 or 3 pre-set stages are provided. Either stage may then be activated from the control center when required. Once the voltage setting is reduced, AVC continues to keep the reduced setting until load reduction is turned off.
- Under-voltage blocking is provided (V_{UV} setting) to prevent the AVC running the OLTC to maximum voltage position during a temporary system disturbance or outage. When power is restored to a substation AVC becomes operational and starts with the OLTC in the position it was in before the outage. This avoids an over-voltage at the restoration of power to the substation. It also prevents sustained over-voltage conditions that could otherwise be caused by a blown VT (voltage transformer) fuse or other failures of the VT supply. Usually the V_{UV} setting is absolute and does not change if V_{SP} changes [1].

The proposed value for the case of study for V_{UV}, V_{OV}, U_{block}, are presented in the table 2.

Table 2

The setting of the blocking values of the AVC using OLTC

No.	Variable	Value	M.U.
1	V_{UV}	198.00	kV
2	V_{OV}	242.00	kV
3	U_{block}	187.00	kV

The on Load Tap Changers (OLTCs) play an important role in long term voltage instability. Simply stated, by restoring distribution voltages to their set-point values, OLTCs restore the power of (voltage dependent) loads to their pre-disturbance values. Voltage instability results when the combined generation and transmission system can no longer deliver this power [4], for instance due to a disturbance Tap changer blocking is thus often cited as an emergency control action against voltage instability [5]. Is recommended that tap changer operations of a transformer should be locked as much as possible, particularly under critical operations in terms of transient stability [6], [7].

3.2. Time delay

The time delay defines the amount of time that should elapse between the moment when measured voltage exceeds the tolerance interval until the appropriate RAISE or LOWER command is issued to the tap changer. The main purpose of the time delay is to prevent unnecessary OLTC operations due to temporary voltage fluctuations and to prevent also the tear of the OLTC [3]. Usually there are two time delays used by the AVC with values between 30 and 120 seconds [1].

First time delay, t_1, is used as a time delay (usually long delay) for the first command in one direction. It can have an inverse time characteristic (large voltage deviations from the V_{SP} value will result in shorter time delays and small voltage deviation from the V_{SP} value result in longer time delays) or a constant time characteristic (an independent time delay of the voltage variation). Usually is used a constant time delay.

Second time delay, t_2, will be used for consecutive commands (i.e. command in the same direction as the first command) and for the fast step down function when the bus-bar voltage exceeds the maxim value. It can have similar time characteristic for the second time delay as for the first time delay [1].

3.3. Line drop compensation

The purpose with the line voltage drop compensation is to control the voltage, not at the power transformer low voltage side, but at a point closer to the load point. Fig. 3 shows the vector diagram for a line modeled as series impedance with the voltage U_B at the low voltage (LV) busbar and voltage U_L at the load center. The load current along the line is I_L and the line resistance and reactance from the station busbar to the load point are R_L and X_L. The angle between the load point voltage and the current is φ_L. If all these parameters are known U_L can be obtained by simple vectorial calculation. Values for R_L and X_L are given as settings in primary system ohms. If more than one line is connected to the LV busbar equivalent impedance should be calculated and given as a parameter setting.

However, the AVC will perform the following two checks:

1. The magnitude of measured busbar voltage U_B, shall be within the security range, $[V_{SP}-V_H,\ V_{SP}+V_H]$. If the busbar voltage falls-out of this range the calculations will be temporarily stopped until voltage U_B comes back within the range.
2. The magnitude of the calculated voltage U_L at the load point, can be limited such that it is only allowed to be equal to or smaller than the magnitude of U_B, otherwise U_B will be used [3].

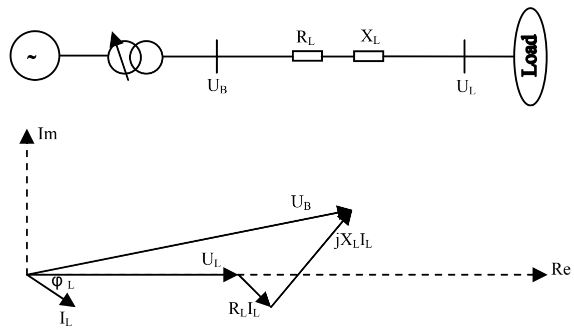


Fig. 3. Vector diagram for line voltage drop compensation [3]

3.4. Case of study

Using a powerful tool of calculation for steady states and transient states, which is ”Eurostag”, it was evaluated the variation of the voltage bus-bar in a very important substation of the transmission network of the Romanian National Power System in different scenarios of operating conditions.

The novelty of the paper subject consist in implementing the automatic local voltage control of a transformer in the national transmission network in which until this moment there is no such regulating solution implemented. The solution of using automatic voltage control is implemented in the distribution network in order to maintatin the voltage of the consumer in tolerable ranges.

The local control is realized through a automatic device attached to the on-load tap-changer. The necessary settings for the AVC device to function properly were presented in the preview section, in table 1 and table 2.

The behavior of the automatic voltage control device and the response of the voltage on the secondary side of the transformer (which is the voltage that should be regulate) are simulated with the Euostag software.

Eurostag is a software that simulates advanced power systems phenomena. It is co-developed by RTE (French Transmission System Operator) and Tractebel engineering. It is based on a powerful algorithm which uses a variable integration step which is automatically adjusted between 1ms and 100s. Il allows the study of a wide range of phenomena from slow dynamics to fast transients [8], [9].

In Fig. 4 is shown the configuration of the substation used for the study case, which is the substation A and also the nearest area of the transmission network, which consist of the substation B, C, D, E, F, G. From this figure it can be also seen that the configuration of the substation A is 1 and ½ circuits breakers on circuit, with five diameters on which are disposed the autotransformers and the lines of the substation.

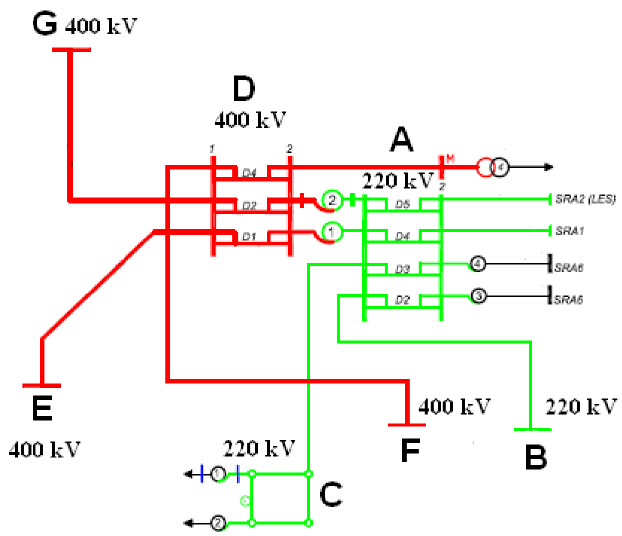


Fig. 4. Study network

In below is analyzed the voltage variation of the substation A in four different scenario of operating conditions which are:

- the line L_{AB}, which is the line with the biggest reactive power which flow into substation A, is disconnected and the autotransformer of the substation A is not equipped with AVC
- the line L_{AB} is disconnected and the autotransformer of the substation A is equipped with AVC
- the power of the customer is decreasing and the autotransformer of the substation A is not equipped with AVC
- the power of the customer is decreasing and the autotransformer of the substation A is equipped with AVC.

In the *first scenario* the autotransformer of the substation A doesn't have a AVC. At the moment t = 10 s the line $L_{A\text{-}B}$ is disconnected because of various reasons, which do not concern the study in case and so are not suggested in this paper. The voltage on the bus of the substation A will reduce its value from 230,79 kV (the value of steady state) to 229,9 kV. Because the autotransformer don't have a AVC device, the system has to deal with a lower voltage than the admissible one which determine a number of inconveniences as the growth of the power losses, growth of equipments stress and a lower quality of electrical energy quality. In the Fig. 5 is shown the voltage variation in the bus A, for de operating conditions mentioned in the first scenario.

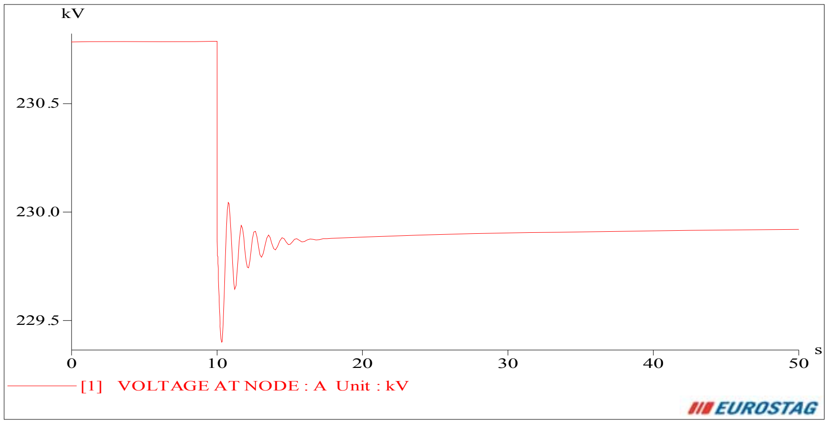


Fig. 5. Voltage variation of the bus A, in the first scenario

In the *second scenario* were simulated the same operating conditions as for the first scenario except the fact that this time the autotransformer of the substation A has a AVC device. After a delay of 30 s the AVC command the tap commutation from the position 1 to position 2 and the voltage level in the bus A is once again in the desired range, with a value of 230,7 kV. The voltage variation for this scenario is shown in Fig. 6.

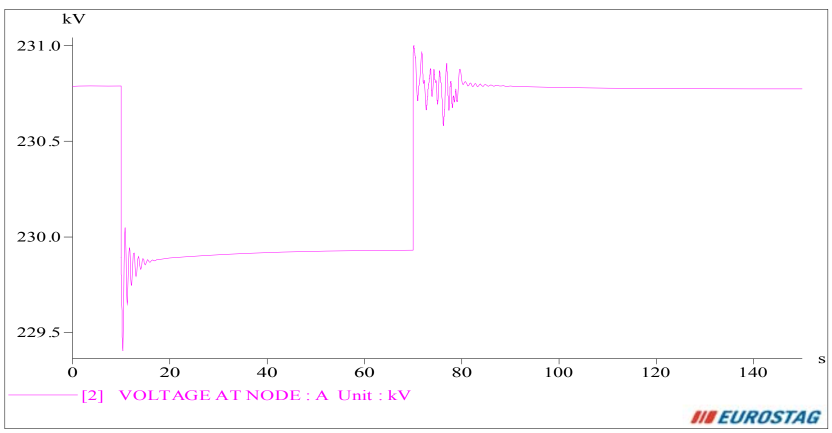


Fig. 6. Voltage variation of the bus A, in the first scenario

In the *third scenario* it was simulated that the consumer reduce its demanded power with 10 %. The voltage on the bus A will rise its value from 230,79 kV (the value of steady state) to 232,15 kV. Because the autotransformer don't have a AVC device, the system has to deal with a bigger voltage value. The simulation results are shown in Fig. 7.

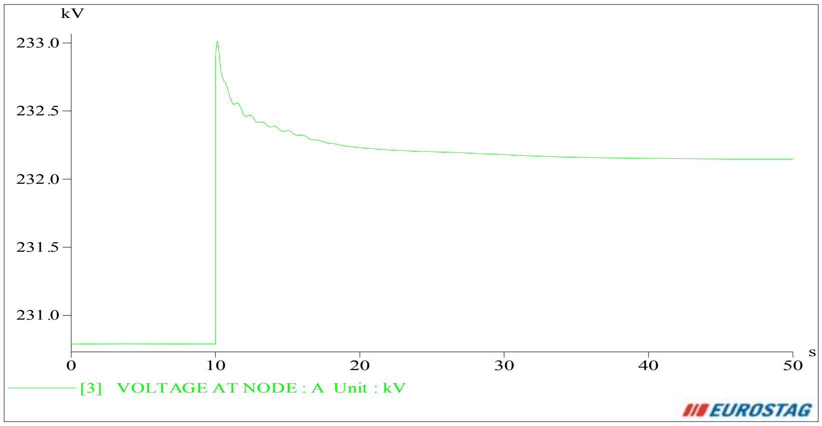


Fig. 7. Voltage variation of the bus A, in the third scenario

In the *fourth scenario* is considered the same disturbance as in the third scenario (the power demanded by the consumer is reducing with 10 % at the time t=10 s) except the fact that the autotransformer has a AVC device. In this case it can be seen that after the set delay of 30 s the AVC command a tap changing from the position 2 to position 3, and the voltage will become 231,34 kV, so it has an admissible value. In Fig. 8 is shown the variation of the voltage in this scenario and in the table 3 the voltage values for the substation A and for the nearest substation for all four scenarios [8].

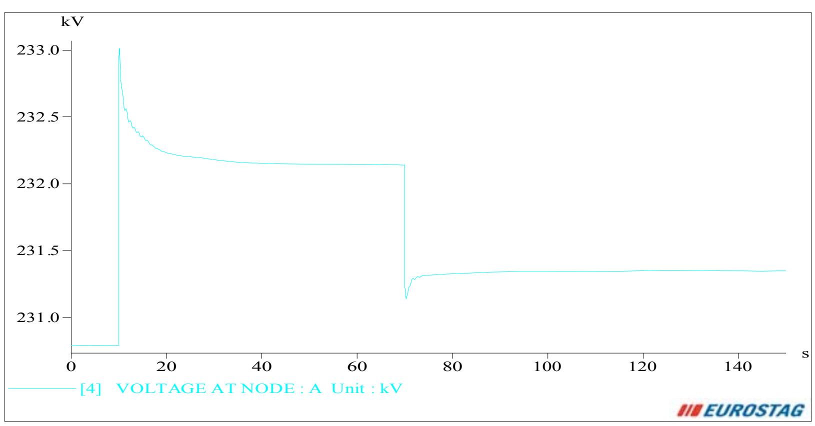


Fig. 8. Voltage variation of the bus A, in the first scenario.

Table 3

The simulation results for the buses voltages in the study network

Substation / Scenario	A 220 kV	B 220 kV	C 220 kV	D 400 kV	E 400 kV	F 400 kV	G 400 kV
	kV	kV	kV	kV	kV	kV	kV
Initial condition	230,79	231,33	230,6	401,29	404,09	406,79	406,46
First scenario	229,9	230,95	229,9	400,77	404,06	406,67	406,37
Second scenario	230,77	230,97	230,77	400,06	404,46	406,53	406,19
Third scenario	232,15	231,9	231,7	402,16	404,66	407,02	406,52
Fourth scenario	231,34	231,5	231,06	402,94	404,84	407,18	406,72

4. Conclusions

The paper had exposed the basic characteristics of the local regulating principle using the on-load tap-changer of the transformers/autotransformers in a High Voltage Power System and the possibilities of implementing this kind of voltage regulation in the transmission network of Romanian Power System, where is not implemented, the studies made by the Transmission Operator for this regulating principle are in progress.

The paper also had proposed the setting values for a AVC device, which was considered to be implemented on a 400/220 kV and 400 MVA autotransformer from a 400/220/110 kV substation of the transmission network of the Romanian National Power System. It should be mentioned that the proposed setting values were establish in order to obtain minimum power loses on the autotransformer. Other reasons of the choosing the settings and the methods used were not specified in this paper because of the different purpose of it. With this setting values implemented in the AVC device associated with the 400 MVAr autotransformer, were simulated with the Eurostag soft different operation conditions. The obtained results aimed to emphasize the important role of the local method for regulating the voltage, which is to maintain a constant voltage level on the low voltage side of the autotransformer (transformer). Because The AVC device maintain a certain voltage level in a bus and hence reduce the power loses in the transmission network, the stress of equipments, and improve the quality of electric energy.

The proposed control method for voltage regulation, the control of OLTC transformers, is aimed at meeting both the demands of the existing power system and future developments of Smart Grid.

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