Automatic Voltage Regulation of the Transformer Units Implemented in Digital Multifunction Protection Systems

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***Abstract-* The paper below present the main features of a digital multifunction protection system and of a voltage control function implemented in this kind of protection system, which control the voltage on the secondary side of a transformer. The paper also analyzes the functionality of a voltage control function included into a multifunction protection system of a 400/220 kV and 400 MVA power transformer unit from a transmission network. The simulation results relieve a prompt and secure action of the voltage control function, maintaining in tolerable ranges the voltage in the specified bus of the study network.**

I. INTRODUCTION

Technology used in relays applied for transformer protection has evolved from discrete electromechanical relays and static relays to digital multifunction protection systems. A lot of protection schemes in service today are single function discrete electromechanical or static relays that have a long history of providing reliable protection. These devices continue to be applied in many applications. However, digital multifunction protection systems (MPS) are now being incorporated into most new protection systems because of their availability, ability to perform most functions, economic advantages, and increased reliability. In most cases, new transformers are being protected with either dual or single multifunction transformer protection systems possibly backed up by some single function relays. Because of the advantages of digital technology, MPSs are being retrofitted on older transformers either to replace the discrete component electromechanical protection schemes, to augment existing protection systems or to add protection functions that were not used on the older transformers. The additional functions that have been become available with the digital technology metering, oscillography, sequence of events capture with time tagging, remote setting and monitoring through communications, user configurability of tripping schemes and other control logic. In spite of these additional functions, the required panel space and wiring is less than needed with the previous technologies, the burden on the VTs and CTs is substantially reduced while the systems have ability for continuous self-checking [1].

II. THE BASICS FEATURES OF A MULTIFUNCTION PROTECTION SYSTEM

Fig. 1 shows the block diagram of a typical multi-function protection system. The system has analog inputs (currents, voltages, temperature etc.), binary inputs, contact inputs for switch status use in the control circuits, and contact outputs for sending trip and alarm signals. An MPS may also have bi-directional communication ports which may use electrical or optical interfaces and protocols, on copper wires, on fiber optic cables or on some other hardware interface for communicating with other devices in the substation and outside the substation. Internal hardware consists of an analog data acquisition system which includes signal scaling, isolating, filtering (anti-aliasing) analog multiplexing, and analog-to-digital converting. The digital subsystem consists of a microprocessor, flash memory for program storage, random-access memory (RAM) for temporary storage of information, and electrically erasable programmable memory (EEPROM) for storage of set points.

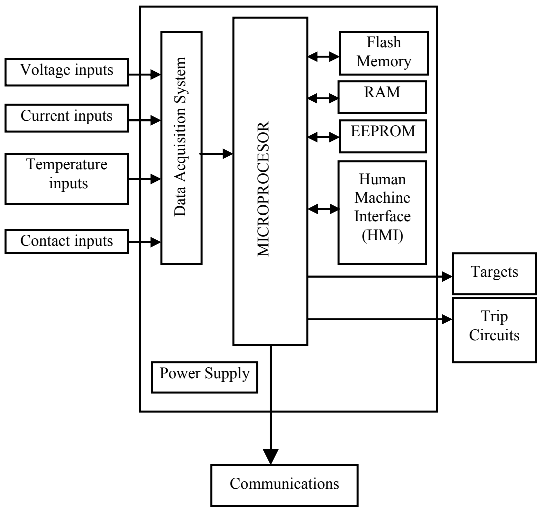

Fig. 1. Block diagram of a typical MPS

The operation and performance of these systems are determined by the hardware of the system and the software-programs used to perform the protection functions. Digital signal-processing algorithms are used to filter the voltage and current inputs and calculate the parameters required for the relaying functions. The relay logic program compares the set points to the calculated parameters and implements the required time delay characteristics. The software program also implements other features such as communication, oscillography, event recording, and local interface with the user. [1]

The drawback is the need of more skilled protection engineers, more settings to be calculated and transferred to the relay, more detailed system analysis and intensive tests of the relay. Even the large amount of technical documentation to be studied and applied represents more than usually needed for classical relays. The need of numerical relay configuration is perhaps the most difficult task for a protection engineer when dealing with numerical relays. Although this feature gives large possibilities to fit numerical relays to any kind of application, configuration takes a lot of time to be implemented and to be carefully tested [2].

III. Typical Protection and Control Function of the Transformers MPS'S

Protective functions integrated into MPS packages include two or more of the following:

- Transformer Differential (87T)
- Restricted earth fault or ground differential protection (87GN)
- Instantaneous and inverse time Overcurrent (50/51)
- Ground instantaneous and inverse time Overcurrent (50G/51G)
- Current Unbalance/Negative Sequence (46)
- Over-excitation (24)
- Under-voltage (27)
- Over-voltage (59)
- Under-frequency (81U)
- Thermal Protection (49)
- Breaker failure (50BF)

The numbers in the parenthesis in the list represent ANSI (American National Standards Institute) device function numbers. Function numbers 27 (Under-voltage) and 81U (Under-frequency) are used for load shedding on distribution transformer applications. Function 46 (Current Unbalance/Negative Sequence) is used to provide sensitive backup for phase to phase faults on a distribution feeder.

A one-line diagram showing typical protection functions included in a multifunction transformer protection system is shown in Fig. 2.

Beside this protection functions a MPS contain also control functions as:

- Voltage control for Power Transformers
- Synchro-check, energizing check and synchronizing
- Apparatus control function
- Event Function
- Disturbance Report
- Remote communication etc.

Among protection functions not frequently used we point out the following:

- Over-excitation protection function. The function is based on the Volt/Hertz criterion and usually covers generation transformer protection.
- Residual high resistance differential protection function. The protection is specialized to protect for winding faults to ground in application where CT saturation could affect normal Differential Protection Function.
- Miscellaneous over current protection functions, negative sequence over current protection functions, under voltage protection functions, etc [2].

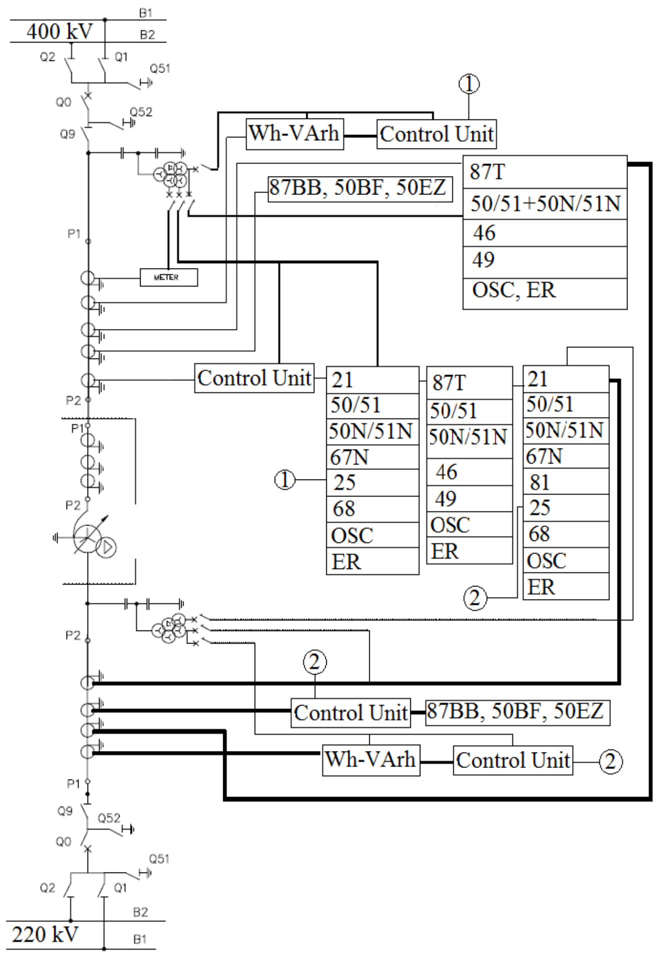

Fig. 2. One-line diagram Block of a typical MPS

IV. Automatic Voltage Control Function Implemented in a MPS

A. Control Principle

The automatic voltage control of the power transformers /autotransformers is made as a step-by-step principle, using an on-load tap-changer (OLTC) equipped with a execution equipment (EE) which is generally a motor-drive mechanisms [3].

In figure 3 is shown the principle method of the automatic voltage regulation of the power transformer /autotransformer and the reactance's scheme:

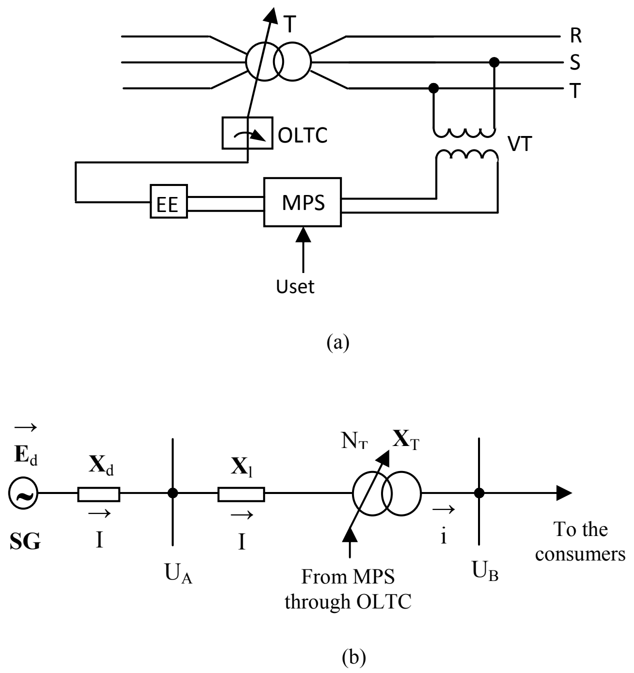

Fig. 3. Automatic voltage control of the transformers / autotransformers: (a) Principle scheme; (b) Reactances scheme.

The execution equipment/the motor drive mechanism actuate over the OLTC modifying step-by-step the tap position and hence the voltage ratio is:

$$N_T = \frac{U_A}{U_B} = \frac{i}{I} \quad (1)$$

If we consider the fig. 3.b, we can write the equations:

$$\underline{u}_{cons} = \underline{u}_B = \left[\underline{E}_d - j\underline{I}(X_d - X_l)\right]\cdot\frac{1}{N_T} - j\cdot\underline{i}\cdot X_{T/B} \quad (2)$$

$$\underline{u}_B = \frac{\underline{E}_d}{N_T} - j\cdot\underline{i}\cdot\left[\frac{(X_d + X_l)}{N_T^2} + X_{T/B}\right] = \underline{E}_d^{'} - j\cdot\underline{i}\cdot\sum X \quad (3)$$

$$\Delta N_T \rightarrow \Delta\left(\sum X\right) \rightarrow \Delta u_B \quad (4)$$

The equations 2, 3 and 4 define the principle of the regulation method, showing how the changing of the voltage ratio influence the customer voltage, U_B.

It is obviously the fact that if N_T is changing the total reactance $\sum X$ of the system will vary and so, the regulated voltage U_B. The secondary impact of the AVC, which concern 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 [3].

The automatic voltage control function principle, integrated in a MPS, is to measure the U_B voltage, on the secondary site of the transformer unit, which is considered the regulated voltage. This voltage is compared to a reference value U_{set} and the necessary commands are decided.

In order to avoid the unnecessary/ insignificant switching around the setpoint, a dead band (i.e. degree of insensitivity) is introduced ($U_{set}+\Delta U \div U_{set} - \Delta U$). The deadband is symmetrical around the Uset value. Inside this interval no tap commands are initiated. The deadband is arranged in such way that there is an outer and an inner deadband. Measured voltages outside the outer deadband starts the timer to initiate tap commands, whilst the sequence reset when measured voltage is once again back inside the inner deadband. The tap commands are initiated are as follows:

- If $U_B > U_{set}+\Delta U = U_2$, it will be initiated a tap change command in order to reduce the voltage U_B, which is the regulated voltage; the sequence repeat, if necessary, until U_B is inside the inner deadband ($U_{set}+\Delta U_{in} \div U_{set}-\Delta U_{in}$), when the sequence reset and the AVC device is once again ready to elaborate another sequence.
- If $U_B < U_{set}-\Delta U = U_1$, it will be initiated a tap change command in order to rise the voltage U_B, which is the regulated voltage; the sequence repeat, if necessary, until U_B is inside the inner deadband ($U_{set}+\Delta U_{in} \div U_{set} - \Delta U_{in}$), when the sequence reset and the MPS device is once again ready to elaborate another sequence [3].

In normal operating conditions (operating in programmed states or very low disturbed) the U_B voltage, considered the regulated voltage, is maintaining natural or by tap changing its value in the interval [$U_1 \div U_2$].

In extreme conditions (operating in very disturbed state) the the U_B voltage, considered the regulated voltage, can achieve inacceptable/dangerous values for the operating conditions and for the equipments in the area – U_{max}: the maximum operating voltage in the bus and U_{min}: the minimum operating voltage in the bus, as the fig. 4 is showing –

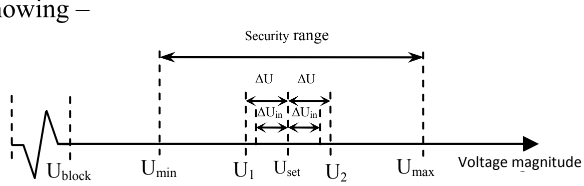

Fig. 4. Voltage scale for illustrating the principle method of the automatic voltage control function of a MPS.

- If the voltage $U_B < U_{min}$ but $U_B > U_{block}$ both manual and automatic commands in order to reduce the voltage are not allowed; manual and automatic commands in order to raise the voltage are allowed;
- If $U_B < U_{block}$, the automatic commands will be blocked but the manual commands are allowed in both directions considering the operating conditions and the possible tap switching that can be done without aggravating the operating conditions which are already disturbed.
- If $U_B > U_{max}$ manual and automatic commands in order to raise the voltage are not allowed; in this case the AVC device can execute more fast step down commands (i.e. Lower commands) in order to bring the voltage into the security range [1], [3], [4].

The logic diagram of the regulation principle for a single transformer is presented in the figure above (fig. 5).

B. *Time delays*

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 on-load tap-changer operations due to temporary voltage fluctuations and to prevent also the tear of the on-load tap-changer [4]. Usually there are two time delays used by the MPS with values between 30 and 120 seconds [1,4].

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 U_{set} value will result in shorter time delays and small voltage deviation from the U_{set} 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].

C. *Blocking modes*

The purpose of blocking is to prevent the tap changer from operating under conditions that can damage the tap changer, or exceed other power system related limits. For a voltage control function three types of blocking could be defined:

- total block
- partial block
- automatic block

Total block prevents any tap changer operation independent of the control mode.

Partial block prevents operation of the tap changer only in one direction (only RAISE or LOWER command is blocked) in manual and automatic control mode.

Automatic block prevents automatic voltage regulation, but the tap changer can still be controlled manually [4].

Tap changer blocking is thus often cited as an emergency control action against voltage instability. 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 [5], [6].

D. *Selection of control location*

Operation mode defines the location from where the tap changer can be manually operated. When operation mode is selected, it is as well important to select manual control mode to enable the voltage control function to issue manual commands.

It is possible to have the following human-machine-interfaces (i.e. HMI) and four operation modes (i.e. locations from where tap changer can be manually operated) for the voltage control function in a MPS:

1. Internal HMI with operation mode (i.e. operation location)
   - MPS built-in HMI
2. External HMI with operation modes (i.e. operation location)
   - Local control panel (usually traditional control panel with selector switches)
   - Station Control (station control system i.e. SCS)
   - Remote Control (SCADA system)

E. *Control mode*

The control mode of the voltage control function included in a MPS can be:

- Manual
- Automatic

The control mode can be changed via the command menu in the built in HMI when the operation mode is “Internal HMI” or changed remotely via binary signals connected to the dedicated inputs on VCTR function block when the operation mode is “External HMI” [4].

F. *Automatic control for parallel transformers*

Parallel control of power transformers means control of two or more power transformers connected to the same bus bar on the low voltage side and in most cases also on the high voltage side.

The following are the main methods of parallel control of transformers.

(a) **Master-Follower control:** this type of control maintains all parallel transformers on the same tap. It works for identical or very similar transformers connected in parallel on both HV and LV sides and also for single-phase transformers in a three-phase bank.

(b) **Circulating Current control:** this type of control minimizes the circulating current between transformers operating in parallel. The transformers do not have to have identical tap steps.

(c) **Reverse Reactance control:** This type of control minimizes the difference in open circuit voltages and hence the circulating current between transformers operating in parallel. The transformers do not have to have identical tap steps but their primary windings do need to be connected directly in parallel. [1]

The automatic voltage regulation function implemented in a MPS could attend to some more issues like load voltage adjustment, power monitoring, manual control of a parallel group and so on, which are not discussed in this paper.

V. CASE OF STUDY

In order to relieve the importance of the local voltage control, maintaining in tolerable ranges the voltages in a specified bus of a power system using a function from a MPS’s power transformer, is considered a network configuration (see fig. 5). The network used for the case of study is part of the Romanian Transmission Network.

In the considered configuration the substation which is monitored is the substation A. The transformer equipped with a MPS (which has a voltage control function implemented) is the 400/220 kV and 400 MVA autotransformer from substation A.

The variation of the bus-bar voltage of the considered transmission network is evaluated for different operating conditions of the system, using the Eurostag program, which is a tool of calculation for steady states and transient states.

The setting parameters of the voltage control function of the MPS modeled with Eurostag are presented in the table 1.

TABLE I
SETTING PARAMETERS OF THE AUTOMATIC VOLTAGE CONTROL FUNCTION IMPLEMENTED IN THE MPS

No.	Variable	Value	M.U.
1	U_{set}	231	kV
2	U_1	230	kV
3	U_2	232	kV
4	ΔU	1.00	kV
5	ΔU_{in}	0.5	kV
6	U_{min}	198	kV
7	U_{max}	242	kV
8	U_{block}	187	kV

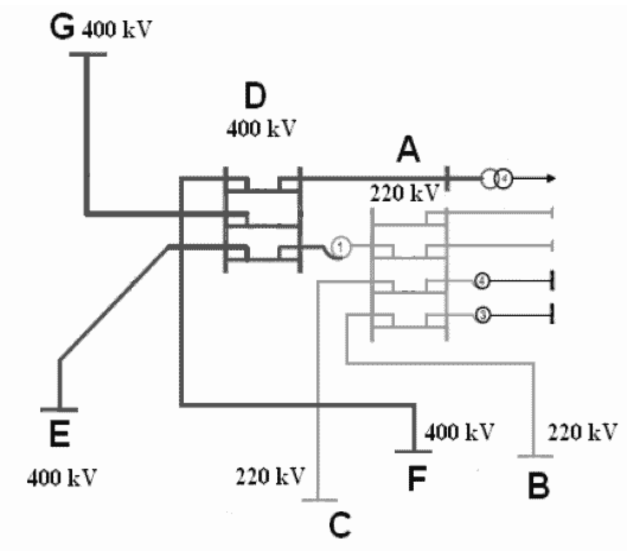

Fig. 5. Study network.

In below is analyzed the voltage variation of the substation A in two scenarios of the operating conditions, which are:

First scenario: the line A-B, which is the line with the biggest reactive power which flow into substation A, is disconnected and the 220/400 kV autotransformer of the substation A is equipped with a MPS with a voltage control function.

Second scenario*:* the power of the customer is decreasing and the autotransformer of the substation A is equipped with a MPS with a voltage control function.

In the *first scenario,* at the moment t =10 seconds the line A-B is disconnected because of various reasons, which do not concern the study in case. After a delay of 30 seconds the MPS 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 [7,8].

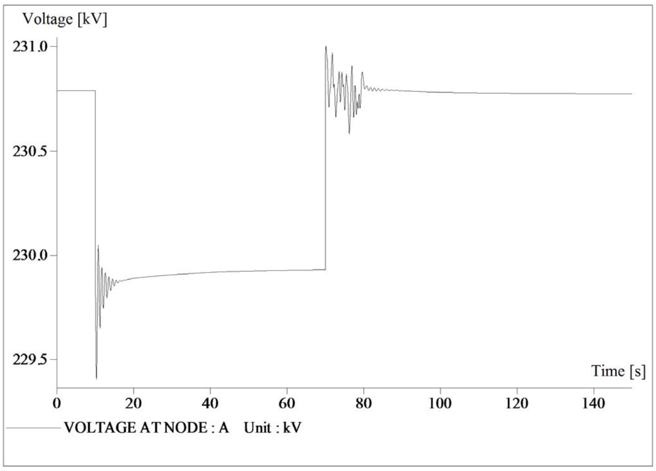

Fig. 6. Voltage variation of the bus A, in the first scenario.

In the *second scenario* it is assumed that the consumer reduce its demanded power with 10 %. The voltage on the bus A will rise its value from 230.7 kV (the value of steady state) to 232.1 kV. In this case it can be seen that after the set delay of 30 seconds the MPS command a tap changing from the position 2 to position 3, and the voltage will become 231,3 kV, so it has an admissible value. In the figure 7 is shown the variation of the voltage in this scenario and in the table II the voltage values for the substation A and for the nearest substation for the analyzed scenarios [7,8].

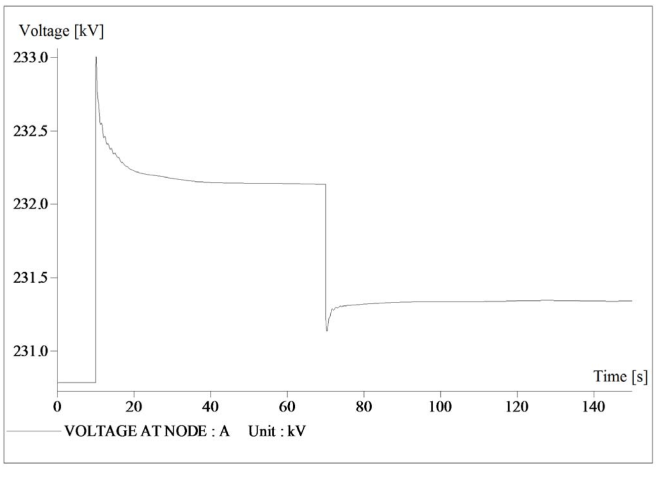

Fig. 7. Voltage variation of the bus A, in the second scenario.

TABLE II
THE SIMULATION RESULTS OF THE BUS VOLTAGES IN STUDY NETWORK

Scenario \ Substation	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	230,7	231,3	230,6	401,2	404,0	406,7	406,4
First scenario	230,7	230,9	230,7	400,0	404,4	406,5	406,1
Second scenario	231,3	231,5	231,0	402,9	404,8	407,1	406,7

VI. CONCLUSIONS

An advanced EHV network voltage control system, which can be achieved through the modern very powerful digital technology and the support of high level software tools and high speed telecommunications, allows to increase the quality, security and economy of the power system operation, besides significant help to the operators in voltage control through high quality and effective voltage [9,10,11,12,13,14].

The paper had exposed the basic characteristics of the voltage control function implemented in a MPS, and reveals a series of advantages of this kind of voltage local regulation using the on-load tap-changer of the transformer units. This advantages regards in the first place short operation times and the possibility to replace a control device – which is needed to control automatically the on-load tap-changer – with a function and so to eliminate a week point of the control system.

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