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Voltage Tap Changer of Power Transformer: Structure, Control and Application

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ABSTRACT

This paper focuses on voltage tap changer of transformers to improve voltage quality in electric power systems. The structure and design of this unit will be mentioned with the capability to change the voltage ratio of the transformer in cases of having electric load at high voltage side and not having electric load at medium voltage side. A method to determine standard voltage taps for both high and medium voltage sides of three-winding transformers will be proposed in this paper to provide information for the controller and execute remote control. Moreover, the control structure of whole system, including local and remote-control modes, will be created for the problem of voltage tap changers. An experimental model will be designed to have a virtual calculation, information display and control signal for the problem of voltage tap. Experimental results will prove the ability to calculate standard voltage taps at high and medium voltage taps of a three-winding transformer using values of voltage source and electric loads. Moreover, voltage taps can be also displayed on a human-machine interface software, LCD screen and send control signal after being evaluated by operators. It helps to show scientific meanings of this research and provide an overview about calculating and controlling voltage taps before applying in real control systems.

Keywords: On-Load tap changer, Load tap changer, Remote control, Voltage quality, Voltage regulator, Voltage tap, Transformer, Three-winding power transformer.

INTRODUCTION

Voltage quality is one of the most important quantities in modern power systems. Many researchers and dispatchers or operators are interested in this problem. Voltage quality can be improved by using the exciter of generators, voltage tap changers, capacitors, renewable power generations or solutions for restructuring whole grids as depicted in Fig.1 [1-2].

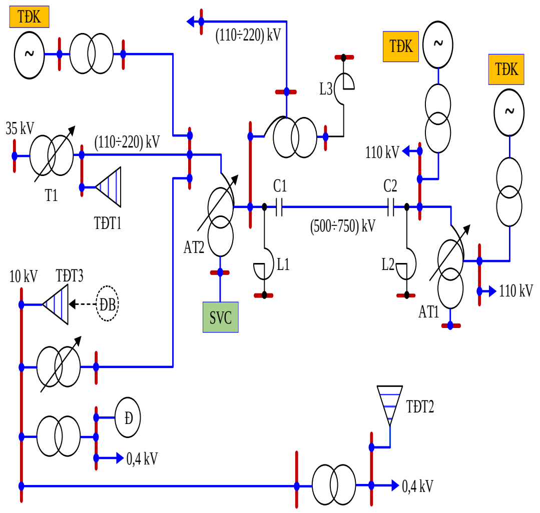


Fig.1 Some solutions to regulate voltage quality in power systems

The exciter of generators only help to regulate voltage quality in a small area around buses having the participation of generators. Capacitors and renewable power generations can be implemented as distributed generations but it makes high cost to invest new devices that has to optimize cost functions [1]. Moreover, these devices must be operated flexibly to dispatch power flows in whole system. Solution for restructuring the grid must be completely created problems of analyzation, control and expert system to restructure whole grid exactly that help to have fast response corresponding to the change of electric loads [1]. Controlling voltage taps of the transformer can be considered as an effective solution because it doesn't require new devices and bring effectiveness suddenly at load sides [2-3]. So, it will be focused to study in this paper.

Voltage at output terminals of the transformer will be regulated by changing its voltage ratio. Voltage tap changer is designed to increase or decrease the number of turns at high voltage (HV) side or medium voltage (MV) side to hold voltage at these side at allowable range. This regulation can be executed by manual or remote control with two types: On-Load Tap Changer (OLTC) or Load Tap Changer (LTC). OLTC allows to regulate with electric loads or without electric loads while LTC requires cutting electric load before regulating. OLTC can help to regulate voltage without disconnecting electric loads (ensuring power quality) [2-13]. Turns at HV and MV sides are often regulated because they have smaller current value than them at LV side which can reduce risks for voltage tap changer.

Voltage taps (TAP) can be controlled by using controllable devices such as FACTS or numerical relay [4-5], mechanical transition [6]. Many researches have shown the meaning of voltage tap changer in improving voltage quality or power quality for the grid [7-13]. Some algorithms were proposed to evaluate the voltage fluctuation or voltage collapse in cases of having integration of the voltage tap changer. Some researches considered the variation of voltage and power vectors before and after controlling [7-13]. However, they have not represented any methods to determine the suitable standard TAP corresponding to the requirement of electric loads and voltage buses at the control time.

This paper will introduce the structure of voltage tap changer and technology to regulate it. A method to determine TAP will be proposed in this paper to provide information for controller and serve remote control. An experimental model will be created to prove the high accuracy of the proposed method. To do this research purpose, section II will introduce the structure and operating principle of voltage tap changer. Section III will represent the remote-control technology for the voltage tap changer and propose a method to determine standard voltage tap. Section IV will represent an experimental model to simulate the calculation process and control signal sending to severe educational training. The last section will show some conclusions and contributions.

Structure and operating principle of voltage tap changer of three-winding transformer

A. Voltage tap changer at high voltage side

For the intermediate transformers, the regulator can be operated and moved by operators or automatic controller in local/remote working modes [2], [7], [9]. In fact, 110 kV transformers can be operated without automatical working mode. The regulator at HV side can be used oil or air vacuum insulation. Advanced control technologies can be applied to increase switching speed. Three-winding transformer, 110/35/22 kV, often has an automatic regulator with 19 TAPs. The structure of voltage tap changer (OLTC) at 110 kV winding side is described in Fig.2 [2].

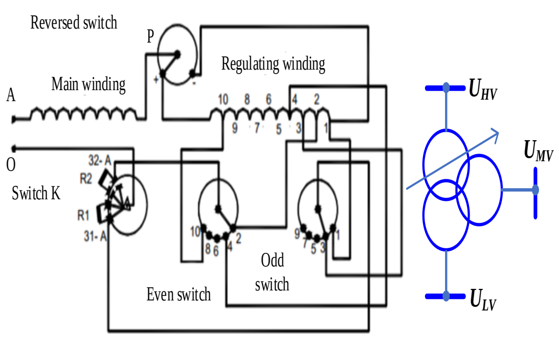


Fig.2 Voltage tap changer at HV winding side of three-winding transformer

Switch P is installed in main oil kettle of the transformer and used to choose even or odd switches.

Switch K is installed in an individual oil kettle and used to slake arc. Switch K works as a circuit breaker with very fast moving speed. Switch K converts rotational movement to straight movement. TAPs of the regulator will work with even system (2, 4, 6, 8, 10) and odd system (1, 3, 5, 7, 9).

A real voltage tap changer of a three-winding transformer is shown in Fig.3. It has a motor and TAP with a switch plate to send feedback location to the controller.

Fig.3 A real voltage tap changer of a three-winding transformer

B. Voltage tap changer at medium voltage side

Normally, regulator at MV side has five TAPs corresponding to $\pm$2,5%U_{rated} [2]. The operating principle is described in Fig.4. If voltage value is stable around rated value, the location of TAP is three. If voltage value is higher than rated value, locations of TAP is two or one. The regulating process is only executed without electric load (de-energized tap changer -DETC). This works the same as two-winding transformers in distribution power system.

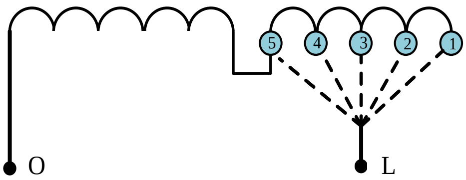


Fig.4 Voltage tap changer at MV side of the three-winding transformer

C. Proposed method to determine standard TAP at HV side

Definition of standard TAP and voltage is shown in TABLE I.

Standard tap and voltage at hv side

Voltage range of standard TAP at HV side (kV)	Location of TAP	
	Theory	Real
96,577	-9	1
$96.577 \le U_{TAP\_HV} < 100.87$	-8	2
$98.624 \le U_{TAP\_HV} < 100.87$	-7	3
$100.87 \le U_{TAP\_HV} < 102.718$	-6	4
$102.718 \le U_{TAP\_HV} < 104.765$	-5	5
$104.765 \le U_{TAP\_HV} < 106.812$	-4	6
$106.812 \le U_{TAP\_HV} < 108{,}859$	-3	7
$108.859 \le U_{TAP\_HV} < 110.908$	-2	8
$110.908 \le U_{TAP\_HV} < 112.953$	-1	9
$112.953 \le U_{TAP\_HV} < 115$	0	10
$115 \le U_{TAP\_HV} < 117.047$	+1	11
$117.047 \le U_{TAP\_HV} < 119{,}094$	+2	12
$119.094 \le U_{TAP\_HV} < 121{,}141$	+3	13
$121.141 \le U_{TAP\_HV} < 123.188$	+4	14
$123.188 \le U_{TAP\_HV} < 125.235$	+5	15
$125.235 \le U_{TAP\_HV} < 127.282$	+6	16
$127.282 \le U_{TAP\_HV} < 128.329$	+7	17
$128.329 \le U_{TAP\_HV} < 131.376$	+8	18
$U_{TAP\_HV} \ge 131.376$	+9	19

Voltage value at HV side can be calculated by (1) [2]:

$$U_{TAP\_HV} = \frac{U_{HV} - (\Delta U_{HV} + \Delta U_{LV})}{U_{LV}} U_{LV\max} \quad (1)$$

When electric loads is maximum, voltage loss at MV side can be calculated by (2) [3]:

$$\Delta U_{MV}^{(2)} = \frac{P_{MV\max} R_{MV} + Q_{MV\max} X_{MV}}{U_{HVrated}} \quad (2)$$

where: P_{MVmax} and Q_{MVmax} are maximum active and reactive power load at MV side; R_{MV} and X_{MV} are resistance and reactance of MV winding; $U_{HVrated}$ is rated voltage of HV side.

When electric loads is maximum, voltage loss at LV side can be calculated by (3) [3]:

$$\Delta U_{LV}^{(2)} = \frac{P_{LV\max} R_{LV} + Q_{LV\max} X_{LV}}{U_{HVrated}} \quad (3)$$

where: P_{LVmax} and Q_{LVmax} are maximum active and reactive power load at LV side; R_{LV} and X_{LV} are resistance and reactance of LV winding.

When electric loads is minimum, voltage loss at LV side can be calculated by (4) [3]:

$$\Delta U_{LV}^{(1)} = \frac{P_{LV\min} R_{LV} + Q_{LV\min} X_{LV}}{U_{HVrated}} \quad (4)$$

where: P_{LVmain} and Q_{LVmin} are minimum active and reactive power load at LV side.

When electric loads is maximum, voltage loss at HV side can be calculated by (5) [3]:

$$\Delta U_{HV}^{(2)} = \frac{(P_{MV\max} + P_{LV\max}) R_{HV} + (Q_{MV\max} + Q_{LV\max}) X_{MV}}{U_{HVrated}} \quad (5)$$

When electric loads is minimum, voltage loss at HV side can be calculated by (6) [3]:

$$\Delta U_{HV}^{(1)} = \frac{(P_{MV\min} + P_{LV\min})R_{HV} + (Q_{MV\min} + Q_{MV\min})X_{HV}}{U_{HVrated}} \quad (6)$$

When electric loads is maximum, voltage value of TAP at HV side can be calculated by (7) [3]:

$$U_{TAP\_HV}^{(2)} = \frac{U_{HV}^{(2)} - (\Delta U_{HV}^{(2)} + \Delta U_{LV}^{(2)})}{U_H} U_{LV\max} \quad (7)$$

When electric loads is minimum, voltage value of TAP at HV side can be calculated by (8) [3]:

$$U_{TAP\_MHV}^{(1)} = \frac{U_{HV}^{(1)} - (\Delta U_{HV}^{(1)} + \Delta U_{LV}^{(1)})}{U_{LV}} U_{LV\max} \quad (8)$$

Standard TAP can be chosen from equation (7) and TABLE I at maximum power load. Standard TAP can be chosen from equation (8) and TABLE I at maximum power load. In cases of different values of power load, standard TAP can be determined same as maximum and minimum loads.

D. Proposed method to determine standard TAP at MV side

When electric loads is maximum, voltage value at MV side can be calculated by (9) [3]:

$$U_{TAP\_MV}^{(2)} = \frac{U_{HV} U_{MV}}{U_{HV}^{(2)} - (\Delta U_{HV}^{(2)} + \Delta U_{LV}^{(2)})} \quad (9)$$

When electric loads is maximum, voltage value at MV side can be calculated by (10) [3]:

$$U_{TAP\_MV}^{(1)} = \frac{U_{TAP\_HV} U_{MV}}{U_{HV}^{(1)} - (\Delta U_{HV}^{(1)} + \Delta U_{LV}^{(1)})} \quad (10)$$

Average voltage value at MV side can be calculated by (11):

$$U_{TAP\_MV} = \frac{U_{TAP\_MV}^{(2)} + U_{TAP\_MV}^{(1)}}{2} \quad (11)$$

Standard TAP can be chosen from equation (11) and TABLE II.

TABLE II. Standard tap and voltage at Mv side

Voltage value of standard TAP at MV side (kV)	TAP	
	Theory	Real
$U_{TAP\_MV} \leq 36.6$	-2	1
$36.6 \leq U_{TAP\_MV} < 37.54$	-1	2
$37.54 \leq U_{TAP\_MV} < 38.5$	0	3
$38.5 \leq U_{TAP\_MV} < 39.45$	1	4
$U_{TAP\_MV} \geq 39.45$	2	5

E. A case study

Considering a three-winding transformer with parameters in TABLE III.

TABLE III. Parameters of a three-winding transformer

S_{rated} (MVA)	U_{rated}			$U_{N\%}$					
	HV	MV	LV	C-T	C-H	T-H	$\Delta P_{N(C-H)}$ (kW)	ΔP_0 kW	I_0%
63	110	38,5	6,3	10,5	17	6,5	270	50,4	0,6

From TABLE III, resistance and reactance of windings can be calculated as following: X_{HV}=20.17 Ω; X_{MV}=0 Ω; X_{LV}=12.48 Ω; R_{HV}=0.206 Ω; R_{MV}=0 Ω; R_{LV}=0.206 Ω.

Consuming that P_{MVmax}=6.8 MW; Q_{MVmax}=4,544 MVAr; P_{MVmin}=2.975 MW; Q_{MVmin}=1,968 MVAr; P_{LVmax}=5.4 MW; Q_{LVmax}=2,615 MVAr; P_{LVmin}=1.8 MW; Q_{LVmin}=0,872 MVAr; $U^{(2)}_{HV}$=107 kV; $U^{(1)}_{HV}$=108 kV.

When electric loads is maximum, voltage loss at MV side can be calculated as:

$$\Delta U_{MV}^{(2)} = \frac{P_{MV\max} R_{MV} + Q_{MV\max} X_{MV}}{U_{HVrated}} = \frac{6.8 \times 0 + 4.544 \times 0}{110} = 0$$

When electric loads is minimum, voltage loss at MV side can be calculated as:

$$\Delta U_{MV}^{(1)} = \frac{P_{MV\min} R_{MV} + Q_{MV\min} X_{MV}}{U_{HVrated}} = \frac{2.975 \times 0 + 1.988 \times 0}{110} = 0$$

When electric loads is maximum, voltage loss at LV side can be calculated as:

$$\Delta U_{LV}^{(2)} = \frac{P_{LV\max} R_{LV} + Q_{LV\max} X_{LV}}{U_{HVrated}} = \frac{5.4 \times 0.206 + 2.615 \times 12.48}{110} = 0.31\ kV$$

When electric loads is minimum, voltage loss at LV side can be calculated as:

$$\Delta U_{LV}^{(1)} = \frac{P_{LV\min} R_{LV} + Q_{LV\min} X_{LV}}{U_{HVrated}} = \frac{1.8 \times 0.206 + 0.872 \times 12.48}{110} = 0.102\ kV$$

When electric loads is maximum, voltage loss at HV side can be calculated as:

$$\Delta U_{HV}^{(2)} = \frac{(P_{MV\max} + P_{LV\max})R_{HV} + (Q_{MV\max} + Q_{LV\max})X_{HV}}{U_{HVrated}} = \frac{(6.8 + 5.4) \times 0.206 + (4.544 + 2.615) \times 20.17}{110} = 1.33\ kV$$

When electric loads is minimum, voltage loss at HV side can be calculated as:

$$\Delta U_{HV}^{(1)} = \frac{(P_{MV\min} + P_{LV\min})R_{HV} + (Q_{MV\min} + Q_{LV\min})X_{HV}}{U_{HVrated}}$$

$$= \frac{(2.975 + 1.8) \times 0.206 + (1.988 + 0.872) \times 20.17}{110} = 0.533\ kV$$

When electric loads is maximum, voltage of TAP at HV side can be calculated as:

$$U_{TAP\_HV}^{(2)} = \frac{U_{HV} - (\Delta U_{HV}^{(2)} + \Delta U_{LV}^{(2)})}{U_{HV}} U_{LV\max}$$

$$= \frac{107 - (1.33 + 0.31)}{6} \times 6.6 = 109.89\,kV$$

The nearest standard voltage value for HV side is 110 kV.

When electric loads is minimum, voltage of TAP at HV side can be calculated as:

$$U_{TAP\_HV}^{(1)} = \frac{U_{HV} - (\Delta U_{HV}^{(1)} + \Delta U_{LV}^{(1)})}{U_{HV}} U_{LV\max}$$

$$= \frac{108 - (0.533 + 0.102)}{6} \times 6.6 = 112.1\,kV$$

The nearest standard voltage value for HV side is 112.953 kV.

When electric loads is maximum, voltage of TAP at MV side can be calculated as:

$$U_{TAP\_MV}^{(2)} = \frac{U_{HV} U_{MV}}{U_{HV}^{(2)} - (\Delta U_{HV}^{(2)} + \Delta U_{MV}^{(2)})}$$

$$= \frac{110 \times 35}{107 - (1.33 + 0)} = 36.43\ kV$$

When electric loads are minimum, voltage of TAP at MV side can be calculated as:

$$U_{TAP\_MV}^{(1)} = \frac{U_{TAP\_MV} U_{MV}}{U_{HV} - (\Delta U_{HV}^{(1)} + \Delta U_{MV}^{(1)})}$$

$$= \frac{110 \times 35}{108 - (0.533 + 0)} = 35.82\ kV$$

Average voltage value at MV side can be calculated as:

$$U_{TAP\_MV} = \frac{U_{TAP\_MV}^{(2)} + U_{TAP\_MV}^{(1)}}{2} = \frac{36.43 + 35.82}{2} = 36.125\ kV$$

The nearest standard voltage value for MV side is 36 kV.

Remote control method and experimental results

A. Remote control method for voltage tap changer

Voltage tap changer works with two main parameters: regulating limitation range and delayed time.

Regulating limitation range is insensitive range. The voltage tap changer will sends control signal if voltage value is out of this range in allowable time range, called delayed time.

Maintaining time is designed to prevent the movement of voltage tap changer in cases of having fluctuations in a short time. It is often chosen from 1 to 3 minutes.

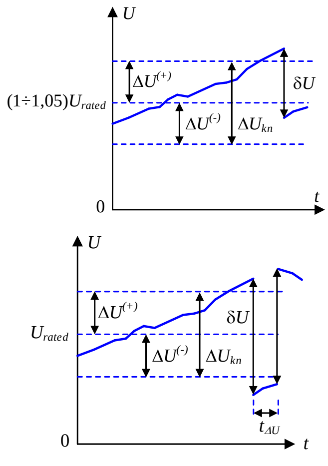
Insensitive range ΔU_{kn} is designed to have regulating step δU as the following condition:

$$\delta U < \Delta U^{(+)} + \Delta U^{(-)} \qquad (12)$$

It is often chosen as the following condition:

$$\Delta U_{kn} = (1{,}1 \div 1{,}2)\delta U \qquad (13)$$

Due to ensuring by this condition, voltage value after regulating is not out of allowable range and automatic controller will be not activated if there is some voltage fluctuation [2], [6] as depicted in Fig.5.



a. $\Delta U_{kn} > \delta U$ b. $\Delta U_{kn} < \delta U$

Fig.5 The change of OLTC corresponding to insensitive range

Operating principle of automatic voltage tap changer type OLTC is shown in Fig.6 [2].

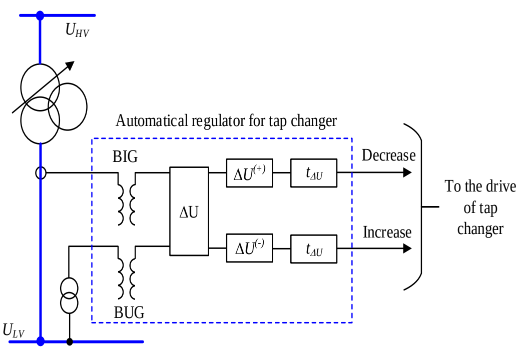


Fig.6 Operating principle of OLTC for three-winding transformer

Information about input signals is collected from a voltage transformer (called VT or BUG) located at LV bus and a current transformer (called CT or BIG) located in series of power circuit.

The regulator can be activated by evaluating voltage deviation ΔU based on:

- Voltage value at the location installed the regulator;
- Voltage value at HV bus and calculating voltage loss in the transformer.

If voltage value at input terminals of BUG is out of allowable voltage range and out of maintaining time, value of U(-) or ΔU(+) will be amplified and calculated to increase or decrease reference voltage value for controller. It means that insensitive range ΔU_{kn} and ΔU(-) or ΔU(+) amplifier and maintaining time will help the voltage tap changer not be activated.

The regulating process can be described in Fig.6. The voltage tap changer can be controlled by manual at locations which is located transformer, control center of the power substation and remote-control center of the utility. Mechanical drive, motors and feedback contacts are installed to rotate the plate into suitable location by receiving control signal. It is noted that controller must be designed to change only a TAP at each time.

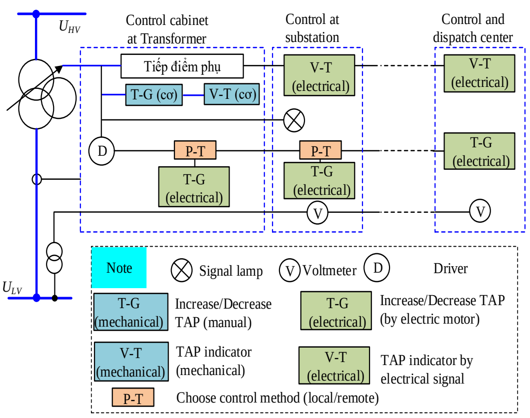


Fig.7 Structure system to operate voltage tap changer in local or remote modes

To choose local operating mode or remote operating mode, the operator must be used a switch at the location implemented the transformer. If the local mode is chosen, the remote mode does not work. If the remote mode is chosen, the local mode does not work. It helps to hold stability for the voltage tap changer and reduce faults caused by control process. The current TAP will be displayed by signal lamps and human-machine interface (HMI) at the power substation and control centers by using the system of auxiliary contacts.

B. Experimental model for educational training and results

This model will use an Arduino Mega 2560 board to work as a central microprocessor. It will collect all information about virtual measurement by using variable resistors, calculate values of voltage and voltage loss and send control signal to turn on/off led indicators. Parameters of the three-winding power transformer are shown in TABLE III. The structure of the experimental model is described in Fig.7.

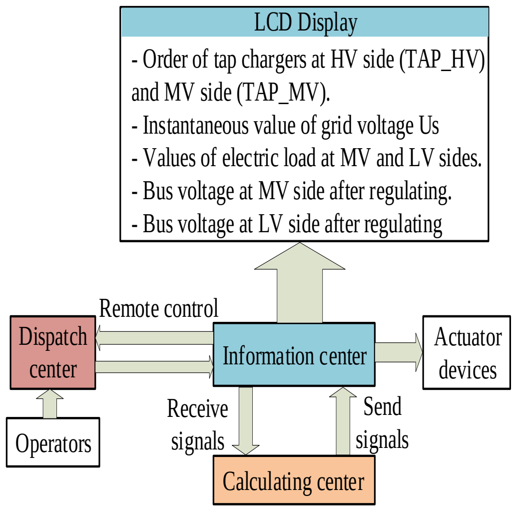


Fig.8 The structure of experimental model

To calculate information and operate above model, an algorithm is proposed as depicted in Fig.9. Method to calculate the location of TAPs at HV and MV sides was proposed in section III.

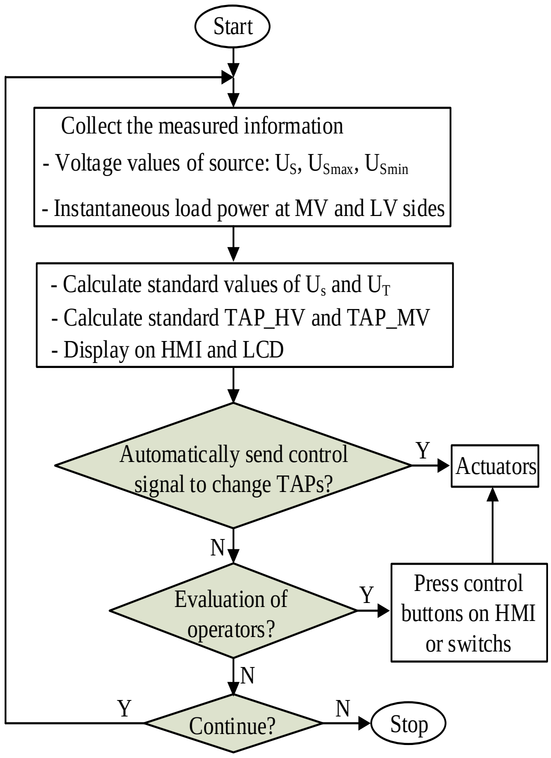


Fig.9 Proposed operating algorithm

Schematic circuit diagram of the experimental model is represented in Fig.10.

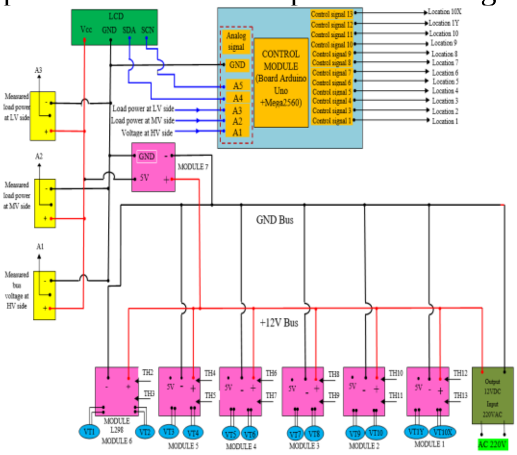


Fig.10 Schematic circuit diagram

A HMI is designed by using Kingview software to control whole system. The operator can type on HMI or regulate variable resistors to adjust information about instantaneous, maximum and minimum values of source voltage; instantaneous values of electric load at MV and LV sides (assuming that power factors are constants). The control and dispatch interface is shown in Fig.11.

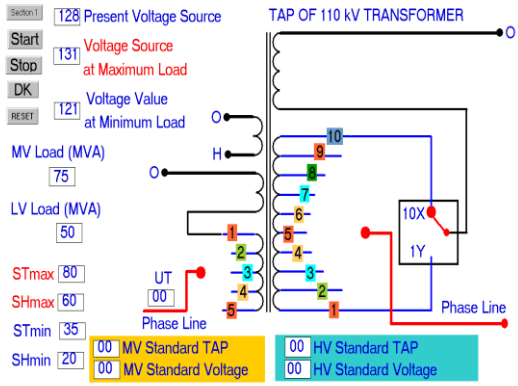


Fig.11 Control and dispatch interface

The microprocessor will calculate standard TAP and standard voltage after the operator types input parameters about source voltage and electric loads and press Start button. The results will be displayed on the HMI but control system is not still activated. It is only activated after the operator press DK button. It means that the microprocessor will send control signal to rotate the motors and the plate to have locations from to 10X or 1Y location; from 1 to 10 at HV side; from 1 to 5 at MV side.

The first case study is considered as: Present voltage source U_S=122 kV; present MV load S_{MV_load}=70 MVA; present LV load S_{LV_load}=50 MVA; S_{MVmax}=80 MVA; S_{MVmin}=35 MVA; S_{LVmax}=60 MVA; S_{LVmin}=20 MVA. The experimental result for this case study is represented in Fig.12, where standard TAP for HV side is 1Y and 2, standard TAP for MV side is 4.

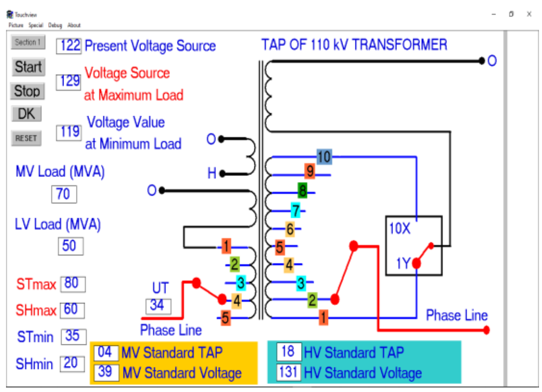


Fig.12 Experimental results for the first case study

The first case study is considered as: Present voltage source U_S=116 kV; present MV load S_{MV_load}=80 MVA; present LV load S_{LV_load}=27 MVA; S_{MVmax}=80 MVA;

S_{MVmin}=35 MVA; S_{LVmax}=60 MVA; S_{LVmin}=20 MVA. The experimental result for this case study displayed on HMI screen (Kingview software) is represented in Fig.13, where standard TAP for HV side is 1Y and 6, standard TAP for MV side is 5.

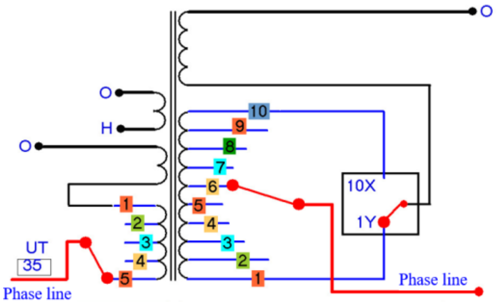


Fig.13 Experimental results for the second case study

In the second case study, results displayed on LCD screen and lamp indicators are represented in Fig.14.

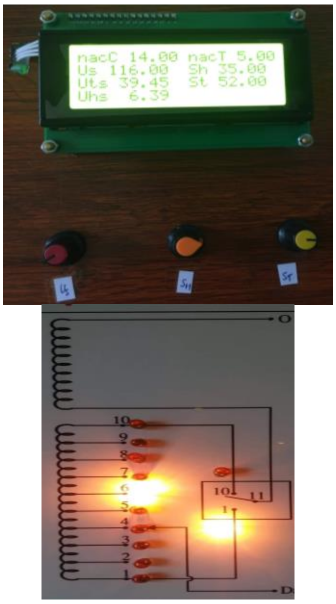


Fig.14 Results displayed on LCD screen and lamp indicators

Above experimental results showed the ability to determine standard TAP for both HV and MV sides of three-winding transformers. They can be calculated, displayed on HMI and LCD screens and lamp indicators. The experimental model described the accurate operation of a tap voltage changer using measured information, a microprocessor, controllable devices, lamp indicators and screens. All experimental results depicted the high accuracy of proposed theory method and created an overview about problem of voltage tap changers in power systems.

CONCLUSION

Voltage tap changer is the main research object in this paper. Its structure and method to control TAP in local/remote operating modes were discussed and created to make clear the way to improve voltage quality for both MV and LV sides of three-winding power transformers. The contribution of this paper is to propose a method to determine standard values for TAP and voltage, including OLTC for HV side and LTC for MV side of a three-winding transformer. OLTC is used to change the number of turns at HV side while electric loads are operating. LTC is used to change the number of turns at MV side while electric loads at MV side are cut off.

Formulas created for voltage tap changer at HV and MV sides of a three-winding power transformer were verified by a theoretical case study and an experimental model for educational training. Results from the theoretical case study provided a detailed calculation about the way to determine desired parameters, program on computer to have a virtual support before implementing and controlling in real system. The experimental model was operated successfully to serve educational training, including a microprocessor Arduino Mega 2560, a HMI, a LCD and actuator devices to simulate the operation of a real system. Experimental results showed the ability to calculate parameters very fast, have some suggests about standard voltage tap changer for the operators. It also help to have a full overview to generally dispatch power systems and individually operate the voltage tap changer of power transformers.

Results received help to affirm the scientific contributions of this paper. Experimental model can be continued to develop by using remote control technologies such as numerical relays and communication. Moreover, artificial intelligence and solutions to improve reliability are also applied in the problem of controlling voltage tap changer. In the future, this problem will be studied more deeply to evaluate the effects of TAPs to whole grid such as power flows, voltage buses, etc.

Declaration by Authors

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Conflict of Interest: The authors declare no conflict of interest.

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