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Evaluation Of The Adverse Effect Of Faulty Potentiometric Universal Controller On Performance Of Power Transformers – A Case Study On 150MVA, 330/132/33kv Substation At Afam Power Station

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Abstract:
Effect of unwanted voltage and temperature variation on a newly commissioned 150MVA, 330/132/33kV power transformer at Afam Power Station, Port Harcourt, Nigeria, was investigated on 3rd-9th February 2019. There were issues relating to the remote display and operation of the Tap-changer and Temperature indicators vis-à-vis field tap position transmitters and temperature Relay transducers. Live tests, simulations and analysis to ascertain and rectify the technical issues arising duly conducted on and off field to give appropriate basis for correction of the anomalies. A Programmable Universal Transmitter SINEAX V 604 which converts the corresponding input signals such as Resistance thermometers, thermo-couples, resistance sensors, potentiometers or DC current or voltage sources, into impressed current or voltage output signals connected to the various measurement locations of the transformer is the target object. Technical failure implications on physical transformer are evaluated and solutions to possible system breakdown suggested.

Background*: The Universal Position Transmitter (SINEAX 604) with an internal micro-controller was exclusively used for the measurement input from potentiometric three-position resistance configuration and the connected field thermometer is Liquid-in-metal expansion type, with lower part of moving indicator equipped with potentiometer slider terminal. Several attempts were made on the field using manufacturer's instructions to achieve variations in temperature but yielded no positive result. It should be noted that the input to the transmitter is purely potentiometric resistance as against PT100 alternative. The field thermometer is Liquid-in-metal expansion type, with lower part of moving indicator equipped with potentiometer slider terminal.*

Materials and Methods*: Off field tests were simulated using a portable multi-function instrument calibrator (PIC-300) to simulate DC Currents and Voltages as well as electronic test board to select proportional resistors. Results were monitored on the Laptop using the installed Manufacturers Configuration Program VC-600. As a result of the erratic behaviour of the instrument prior to adjustments, it became obvious that we investigate the type of output coming out in this configuration (voltage or current), so we interchanged the program output from current to voltage and vice-versa and the corresponding results gave us the key to the needed solution.*

Results*: Results of tests conducted on the field gives the required values of resistors, peak output currents and tap-positions/temperatures before and after adjustments both in and outside control room. Tests conducted in our workshop without any adjustments on the various transducers gave us insight into the behaviour of the transducers. Several off-field parameter manipulations and Program Simulations as presented gave us key and insight into the actual problems on the field.*

Conclusion: *Appropriate technical issues are evaluated with On-field adjustments/replacement to faulty components made, problem was rectified and the transformer successfully commissioned as per design and specifications.*

Keywords*: Universal Position Transmitter, potentiometric transmitter resistors, analogue current transducer (4 – 20mA), position indicators, temperature indicator transducer, autotransformer, on-load tap changer, breaking strength, tie-in resistor, recovery voltage, out-rush current, back-t0-back switching.*

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I. Introduction

Monitoring of power systems with respect to the main elements such as generators, transformers, lines, and substations, is essential to their operation and safety. Many applications are used to enhance a more sophisticated operation and diagnosis of power systems. Power transformers belong to the most valuable assets in electrical power networks and the outage impacts of the network resulting from transformers with associated financial penalties for the power systems can be considerably high. Monitoring of transformers consist the measurement of basic parameters with threshold alarms. Therefore, integration and collection of data from local control functions and early warning of incipient failure symptoms are necessary, and it provides the first indicator that the transformer has exceeded a previously established threshold value. Two aspects of transformer monitoring is under consideration in this write-up – thermal modelling and tap position control.

II. Transformer Operating Parameters

The operating parameters are still the same, no matter the type or capacity. These can be divided into eight groups and are posted on the nameplate of any transformer of significant size: VA rating, cooling (or temperature models), transformer rating, frequency, voltage, phase, connections, and taps. We shall limit ourselves to only two of the parameters in this consideration within the confines of our focus. Tap-changer Control and Health Monitoring System is a Customized control and monitoring of On-load tap-changers. Automatic voltage regulation based on voltage point set, time delay. It involves Multiple voltage set-points based on load can be set, Monitors oil, winding, OLTC temperatures, oil level, flow etc. and tap-change activity. It also monitors and controls cooling equipment based on temperature/ load Diagnostic features like DGA, moisture measurement etc. hotspot temperature calculation and other special features can be incorporated. Discussions on the implication of failures will be evaluated at the end of this write-up.

Transformer Temperature Models

The useful life of a transformer is determined partially by the ability of transformer to dissipate the internally generated heat to its surroundings. The comparison of actual and predicted operating temperatures can provide a sensitive diagnosis of the transformer condition and might indicate abnormal operation. The consequences of temperature rise may not be sudden, but gradual as long as it is within break down limit. Among these consequences, insulation deterioration is economically important and because it is very costly, its deterioration is undesirable. Thermal modeling as the development of a mathematical model that predicts the temperature profile of the power transformer using the principle of thermal analysis, is used to determine the top oil temperature and hot spot temperature.

As electro-mechanical switching equipment operating within tap-changing positions of power transformers, the operational principle of tap changers is based on a sequence of switching events within certain timing intervals depending on voltage fluctuations, optimization processes, overhead power lines synchronization, and other load conditions in the power system. This operation is carried out by changing the transformer ratio using tapped windings to compensate variations of the voltages and loads, and the parameter is significant in minimizing the number of power system outages and load interruptions. Based on statistics and surveys, tap changers are considered as the key factors in most transformer failures.

III. Universal Transmitters:

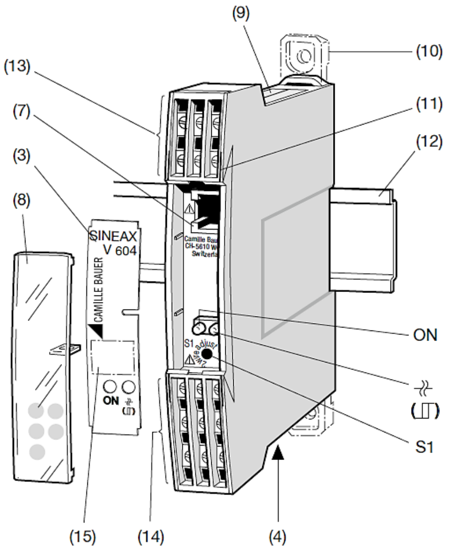
In the field of process control system, a universal transmitter refers to a versatile device used to measure and transmit various types of process variables or signals. It is designed to accept inputs from different types of sensors or transducers and convert them into a standardized output signal, typically in the form of a current loop (e.g., 4-20mA) or digital communication protocols like Highway Addressable Remote Transducer (HART) or Foundation Fieldbus. Universal transmitters are often used in industrial applications to monitor and control parameters such as temperature, pressure, level, flow, position etc.

The universal transmitter is able to accommodate an input signal from a wide variety of external sensors, including current, voltage, resistance and temperature devices. This feature makes the transmitter ideal for applications using large numbers of sensors (where vibration sensors are from Industrial Measurement Instrumentation (IMI) Sensors, but temperature and resistance sensors are from a third-party manufacturer) that want a single unified transmitter product.

Each transmitter can only receive a single input signal so transmitters and external sensors must be set up in a one-to-one ratio. Dual output external sensors must be paired with two transmitters, one to handle the vibration or position signals and one to handle the temperature signal. It is also important to understand that each of the two models can only accept select input signals. The table below provides a matrix of the input type availability based on universal transmitter model number.

Universal Transmitter SINEAX V 604:

Figure 1 shows those parts of the transmitter of consequence for mounting, electrical connections, programming connections and other operations described in the Operating Instructions.



(3)	Front plate
(4)	Type label (operating data)
(7)	Programming connector
(8)	Transparent cover
(9)	Type label (device ratings)
(10)	Fixing bracket
(11)	Opening for withdrawing clip (for opening the housing)
(12)	Top-hat rail 35×15 mm or 35×7.5 mm (EN 50 022)
(13)	Terminals 1, 2, 6, 7, 11, 12 measuring input M
(14)	Terminals 4, 9 measuring output A1 3, 8 measuring output A2 5, 10 power supply H 13, 14, 15 output contact K
(15)	Space for notes
S1	Calibration button for automatically compensating the leads of two-wire resistance thermometer circuits
ON	Green LED for signalling operating statuses
⫲	Red LED for open-circuit sensor supervision or
⎍	as relay status signal (open-circuit sensor supervision not in operation)

Figure 1: Parts of SINEAX V 604 Universal Transmitter

Resistance thermometers, thermo-couples, resistance sensors, potentiometers, or DC current or voltage sources are connected to the programmable universal transmitter SINEAX V 604 which then converts the corresponding input signals into impressed current or voltage output signals. Measured variables and measuring ranges are programmed with the aid of a PC, a programming cable and the programming software. Specific measured variable data such as output signal, transmission characteristics, active direction and open-circuit sensor supervision data is also programmed.

The output signals can be either load-independent DC currents IA or DC voltages UA. The desired mode is set on DIP switches and the setting range is programmed on a PC. A1 and A2 are not DC isolated, and the same value is available at both outputs.

Standard ranges for I_A : 0...20 mA or 4...20 mA

External resistance I_A: R_{ext} max. [kΩ] = $\frac{15\text{V}}{I_{AN}\,[\text{mA}]}$

resp. = $\frac{-12\text{V}}{I_{AN}\,[\text{mA}]}$

I_{AN} = Full-scale output current value

External resistance I_{A2} : R_{ext} max. [kΩ] = $\frac{0.3\text{V}}{I_{AN}\,[\text{mA}]}$

Standard ranges U_A : 0...5, 1...5, 0...10 or 2...10 V

Load capacity U_{A1} / U_{A2} : R_{ext} [kΩ] ≥ $\frac{U_A[\text{V}]}{20\text{mA}}$

IV. Tap-position Transmitter and Indicator:

The Position Indicator performs the on-load tap changer position measurement in order to make this information available to the user. This measurement is accomplished by a Position Indicator input, specific for connecting a potentiometric **position transmitter** of the on-load tap changer.

The Universal Position Transmitter (SINEAX 604) is provided by an internal micro-controller exclusively dedicated to the necessary calculation for the tap position measurement, verification of its consistency and compensation of the measurement input from potentiometric three-position resistance configuration. Tap measurement input: terminals 6, 1, and 11 (cursor, start and end, respectively) provide the needed measurement input to the transmitter.

The on-load tap changer position transmitter is of the potentiometric type, with its resistance changing from zero to the maximum value for the start and finish tap changer positions respectively. This particular tap changer has "intermediary" position at tap 9, namely, transition positions that have the same voltage of other adjacent positions, as shown in table 1 below. The resistors of the potentiometric crown relative to these positions are removed and/or short circuited, as shown in the diagram of figure 1. All the intermediary positions (9A, 9B and 9C) will be indicated as tap "9".

The SINEAX 604 universal transmitter input terminals 1, 6 and 11 accept resistance by potentiometric transmitter step (the value of each individual transmitter shown in the figure 1).

TABLE 1: DETAILS OF TAP-CHANGER TRANSITION POSITIONS

Tap Position	Voltage (V)	Current(A)	Resistance Cursor/Initial Position (example for 10Ω/step)
1	346500	249.9	0
2	342375	252.9	10
3	334755	258.8	20
4	334125	259.2	30
5	330044	262.4	40
6	325875	265.8	50
7	321750	269.2	60
8	317625	272.7	70
9A	313500	276.2	80
9B			80
9C			80
10	309375	279.9	90
11	305250	283.7	100
12	301125	287.6	110
13	297000	291.6	120
14	292875	295.7	130
15	288750	299.9	140
16	284625	304.3	150
17	280500	308.7	160

The transducer has an analogue output in current loop (4 – 20mA) for remote indication of the tap changer position. The current output value range is selected using a customised programming software, and output per tap position is proportional to the input to the transducer. Until accurate proportionate value is achieved on a linear rising scale accurate indication cannot be achieved on the panel in the control room.

The initial problem of the tap changer was that the tap transition resistors were wrongly installed. 100Ω resistors were installed instead of 10Ω resistors. This was subsequently corrected as 10Ω resistors were used to replace the 100Ω resistors. The transducer configuration software was then utilized to program and parameterize it. The final settings of the program software are given in table 2 below.

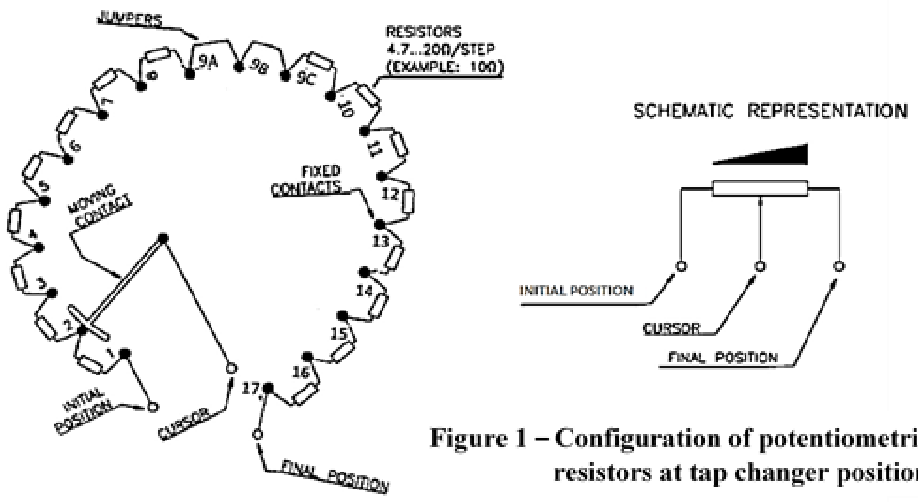
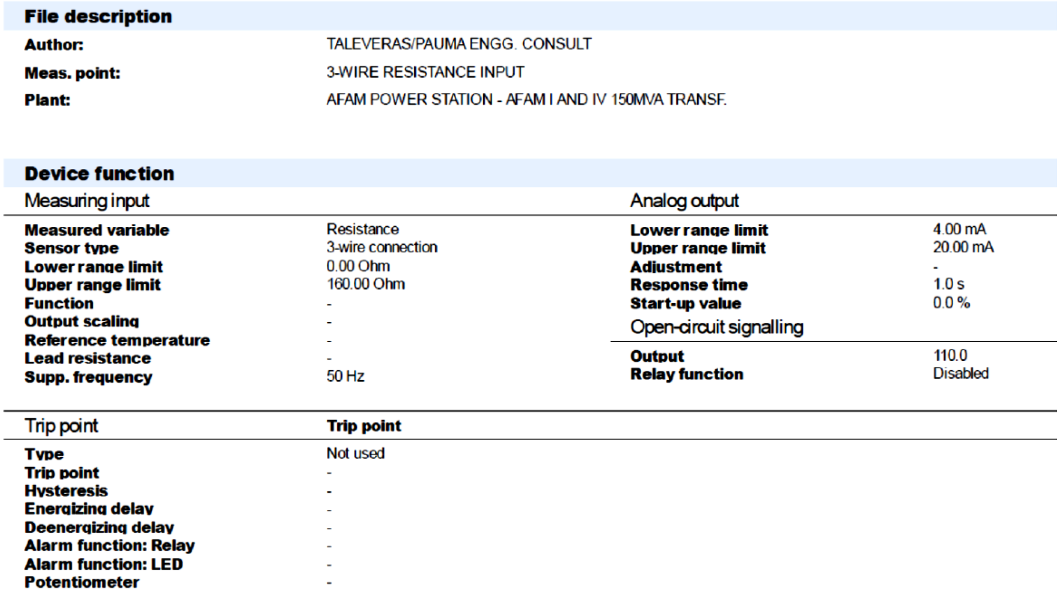


Figure 1 – Configuration of potentiometric transmitter resistors at tap changer positions

Table 2: Tap Changer Transmitter (U1) Program Settings



File description

Author:	TALEVERAS/PAUMA ENGG. CONSULT
Meas. point:	3-WIRE RESISTANCE INPUT
Plant:	AFAM POWER STATION - AFAM I AND IV 150MVA TRANSF.

Device function

Measuring input		Analog output	
Measured variable	Resistance	**Lower range limit**	4.00 mA
Sensor type	3-wire connection	**Upper range limit**	20.00 mA
Lower range limit	0.00 Ohm	**Adjustment**	-
Upper range limit	160.00 Ohm	**Response time**	1.0 s
Function	-	**Start-up value**	0.0 %
Output scaling	-	Open-circuit signalling	
Reference temperature	-		
Lead resistance	-	**Output**	110.0
Supp. frequency	50 Hz	**Relay function**	Disabled

Trip point	**Trip point**
Type	Not used
Trip point	-
Hysteresis	-
Energizing delay	-
Deenergizing delay	-
Alarm function: Relay	-
Alarm function: LED	-
Potentiometer	-

The corresponding expected virtual output characteristic for various tap positions up to tap 17 is shown in figure 2 below.

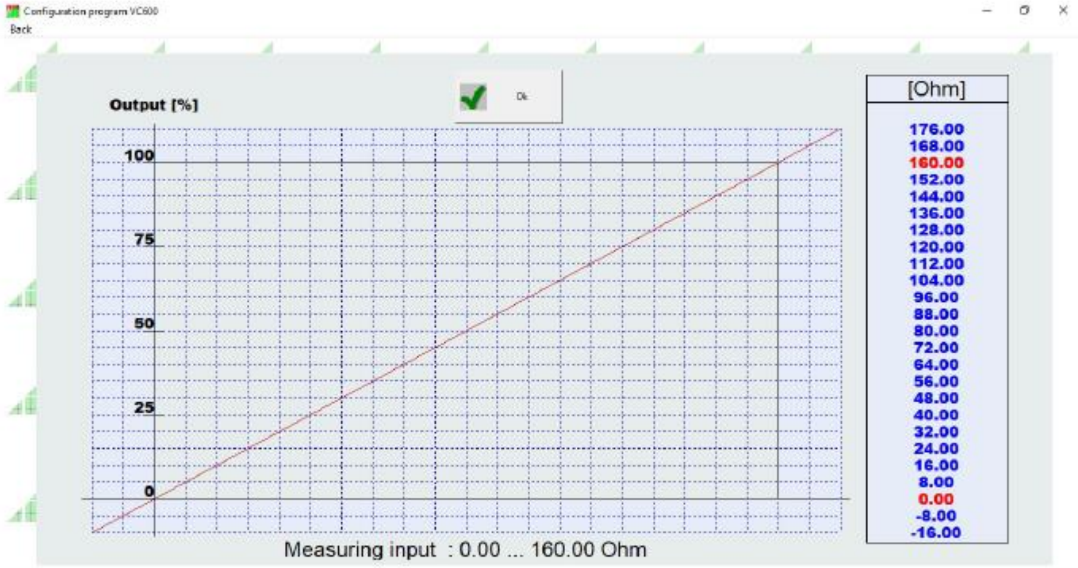


Figure 2: Simulated Tap-changer Virtual Output Characteristic

The current output was expected to change linearly inside the selected range, proportionally to the respective tap positions. This way, the output value for a given tap position can be calculated by the simple formula as follows:

$$\text{mA output} = \frac{(\text{mA end scale}) - (\text{mA begin of scale})}{(\text{Final Tap}) - (\text{Initial Tap})} \times (\text{Present Tap} - \text{Initial Tap}) + (\text{mA begin of scale})$$

The data from this calculation is given in table 3 below, and the corresponding curve for U1 is given in figure 3 below.

Table 3: Actual Output Current against Tap Position of Tap Changer

TAP POSITION	Current (mA) End of Scale	Current (mA) Begin of Scale	Initial Tap	Final Tap	Current (mA) Output	REMARKS
1	20	4	1	17	4	THE OUTPUT RESULTS IN A LINEAR RISING SCALE CORRESPONDING TO RESPECTIVE POTENTIOMETER INPUT
2					5	
3					6	
4					7	
5					8	
6					9	
7					10	
8					11	
9					12	
9					12	
9					12	
10					13	
11					14	
12					15	
13					16	
14					17	
15					18	

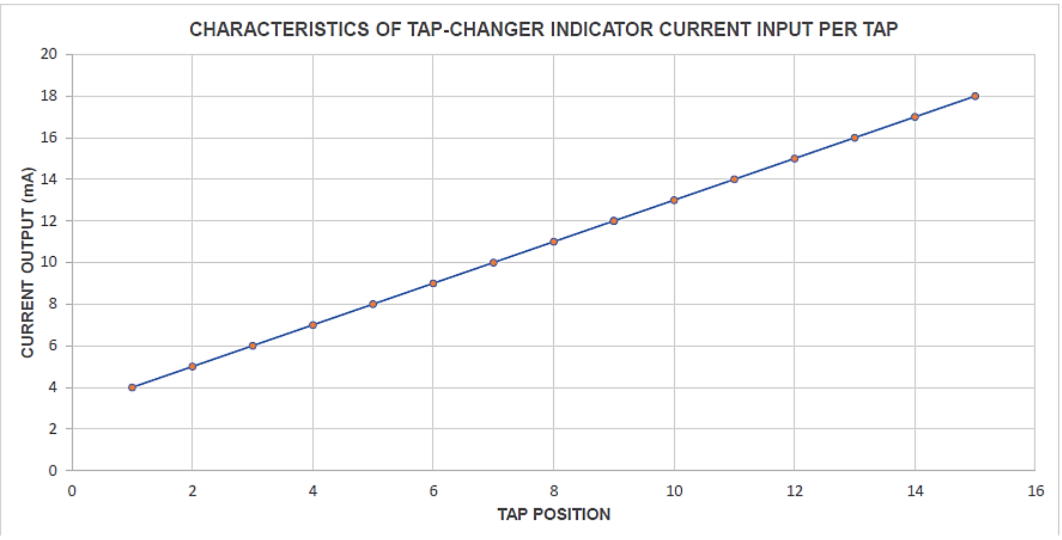


Figure 3 – Actual Characteristic of Tap-changer indicator current from Field Transmitter

Necessary adjustments made to establish the set-points and implement the relevant incremental tap positions as against original settings are shown in table 4 below.

After achieving the correct resistance matching, it was observed that the tap positions were swapped. Tap 1 on the field was found as tap 15 on the control room indicators and tap 15 on the field indicated tap 1 in the control room. In other to correct these anomalies, Resistance input terminals to the transducer were selected through combinational mappings. Details of the Tap Changer Troubleshooting process is given in Table 4.

TABLE 4: TAP – CHANGER TROUBLESHOOTING & REPAIRS

Tap Position	Resistance Values/Initial Position (Ω/step)				Transmitter Output Voltage (mA)		Control Room Indicator (Tap Position)		REMARKS
	MDU Rotary Switch		Transmitter Input						
	As Found	As Left	As Found	As Left	As Found	As Left	As Found	As Left	
1	0	0	0	0	29.5	4	18	1	The entire System was Restored to Norma Operating Condition.
2	100	10	98	12.2	29.5	5	18	2	
3	200	20	196	24.4	29.5	6	18	3	
4	300	30	294	36.6	29.5	7	18	4	
5	400	40	392	48.8	29.5	8	18	5	
6	500	50	490	61.0	29.5	9	18	6	
7	600	60	588	73.2	29.5	10	18	7	
8	700	70	686	85.4	29.5	11	18	8	
9A	800	80	784	97.6	29.5	12	18	9	
9B									
9C									
10	900	90	882	109.8	29.5	13	18	10	
11	1000	100	980	122.0	29.5	14	18	11	
12	1100	110	1078	134.2	29.5	15	18	12	
13	1200	120	1176	146.4	29.5	16	18	13	
14	1300	130	1274	158.6	29.5	17	18	14	
15	1400	140	1372	170.8	29.5	18	18	15	

V. The Temperature Indicator Transducers:

One of the major problems encountered with the SINEAX 604 field temperature transducers (U2 – U5) was the programming data mismatch. The physical DIP Switch settings for programming current and voltage outputs did not agree with the software commands.

Of the programmable details listed in the manual, **one parameter** – the **output signal** MUST be determined by PC programming as well as **mechanical setting of DIP Switches** on the transmitter unit.

(a) … the output signal range by PC
(b) … the type of output (current or voltage signal) has to be set by DIP switch (see Figure 4).

DIP switches	Type of output signal
	load-independent current
	load-independent voltage

Figure 4a: DIP Settings recommended by Manufacturers

DIP switches	Type of output signal
	load-independent current
	load-independent voltage

Figure 4b: DIP Settings Implemented on the Field
Figure 4: DIP Switch Settings

By default and design, the measured variable M is stepped down to a voltage between –300 and +300 mV in the input stage. The input stage includes potential dividers and shunts for this purpose. A constant reference current facilitates the measurement of resistance. Depending on the type of measurement, either one or more of the terminals 1, 2, 6, 7 and 12 and the common ground terminal 11 are used.

The constant reference current which is needed to convert a variation of resistance such as that of a resistance thermometer, remote sensor or potentiometer to a voltage signal is available at terminal 6. The internal current source automatically sets the reference current to either 60 or 380 µA to suit the measuring range. The corresponding signal is applied to terminal 1 and is used for resistance measurement.

Expectedly, these two current levels set the needed potentiometric input levels at terminals 1, 6, and 11 for the internal comparators and level detectors as illustrated in figure 5 below.

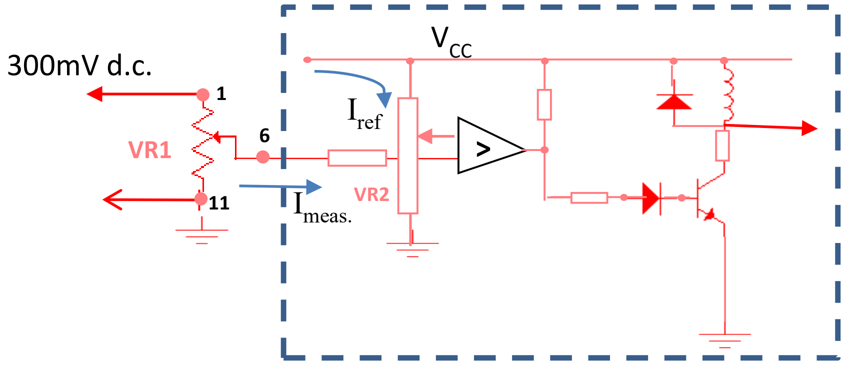


Figure 5: Principles of Potentiometric Input Measurement

Therefore, the maximum peak values that can be applied at the input section as given by:
For I = 60μA, $VR_1 = 300\text{x}10^{-3}/60\text{x}10^{-6} = 5{,}000\Omega$
For I = 380μA, $VR_1 = 300\text{x}10^{-3}/380\text{x}10^{-6} = 789.47\Omega$

This explains why ranges for measured variables are fixed as follows:
R_m = 0 – 740 for Low Resistance Range
And R_m = 0 – 5000 for High Resistance Range

Several attempts were made on the field using manufacturer's instructions to achieve variations in temperature but yielded no positive result.

It should be noted that the input to the transmitter is purely potentiometric resistance and not PT100 as earlier assumed. The field thermometer is Liquid-in-metal expansion type, with lower part of moving indicator equipped with potentiometer slider terminal. Results of tests conducted on the field gives the values of resistors, peak output currents and temperatures before and after adjustments both in and outside control room as shown table 5. On-field equipment Calibration and Programming were conducted as shown in the picture of figure 6.

TABLE 5: UNIVERSAL TRANSMITTER TROUBLESHOOTING & REPAIRS (Temperature Indicators)

Measured Parameter		Transmitter Designation			
		U2	U3	U4	U5
Input Resistance (Ω)	As Found	332	404	333	332
	As Left	332	404	332	332
Field Indicator		32^0C	34^0C	34^0C	37^0C
Max. Output Voltage (V)	As Found	18	18	18	18
	As Left	14.45	14.05	13.35	13.57
Control Room Indicator		158^0C	157^0C	156^0C	155^0C
Max. Output Current (mA)	As Found	31.07	29.76	29.66	29.45
	As Left	21.49	21.54	21.55	21.57
Control Room Indicator		158^0C	157^0C	156^0C	155^0C
REMARKS		ISSUES WITH ALL PEAK VALUES HAVE BEEN RECTIFIED WITH DIP SWITCH ADJUSTMENTS			

Off field, this arrangement was simulated using electronic test board to select proportional resistors as shown in figure 7.

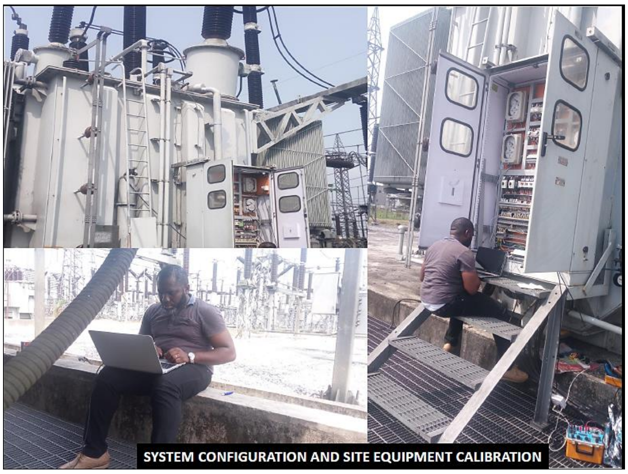


Figure 6: Site Equipment Calibration and Programming of SINEAX 604

Figure 7: Workshop Programming and Simulation of SINEAX 604 Operating Characteristics

Tests conducted in our workshop as shown in figure 7 above without any adjustments on the various transducers gave us insight into the behaviour of the transducers as illustrated in table 6 and figures 8 – 9 below.

Table 6: Test Reports on Temperature Transmitter SINEAX 604 before adjustments

LINEAR 3-WIRE RESISTANCE

MEASURING RANGE (Ω)	MEASURED INPUT (Ω)		TRANSMITTER OUTPUT AT 0 - 20mA SETTING (mA)							
	TERMINAL 1-6	TERMINAL 6-11	U2		U3		U4		U5	
			VALUE	%	VALUE	%	VALUE	%	VALUE	%
OPEN CIRCUIT	>160	0	31.07	100	29.76	100	29.66	100	29.45	100
0 – 500	160	0	32.94	106.02	5.5	18.48	6.5	21.92	2.5	8.49
	100	10	32.75	105.41	29.45	98.96	29.3	98.79	29.13	98.91
	50	30	32.37	104.18	29.56	99.33	29.34	98.92	29.17	99.05
	30	50	31.99	102.96	29.57	99.36	29.42	99.19	29.22	99.22
	10	100	31.04	99.90	29.61	99.50	29.47	99.36	29.3	99.49
	0	160	30.85	99.29	29.64	99.60	29.51	99.49	29.32	99.56
0 – 740	160	0	32.9	105.89	5	16.80	7.5	25.29	2.08	7.06
	100	10	32.77	105.47	29.4	98.79	29.33	98.89	29.15	98.98
	50	30	32.5	104.60	29.45	98.96	29.38	99.06	29.2	99.15
	30	50	32.25	103.80	29.49	99.09	29.42	99.19	29.24	99.29
	10	100	31.63	101.80	29.52	99.19	29.45	99.29	29.27	99.39
	0	160	30.92	99.52	29.55	99.29	29.48	99.39	29.29	99.46
0 – 1000	160	0	32.8	105.57	2.5	8.40	6	20.23	1.65	5.60
	100	10	32.7	105.25	29.46	98.99	29.34	98.92	29.16	99.02
	50	30	32.52	104.67	29.51	99.16	29.4	99.12	29.22	99.22
	30	50	32.33	104.06	29.54	99.26	29.44	99.26	29.24	99.29
	10	100	31.86	102.54	29.56	99.33	29.47	99.36	29.26	99.35
	0	160	31.31	100.77	29.58	99.40	29.5	99.46	29.28	99.42
0 – 5000	160	0	32.77	105.47	2.1	7.06	7	23.60	1.23	4.18
	100	10	32.75	105.41	29.51	99.16	8.5	28.66	7.5	25.47
	50	30	32.72	105.31	29.54	99.26	28.4	95.75	20.5	69.61
	30	50	32.67	105.15	29.56	99.33	29.45	99.29	29.1	98.81
	10	100	32.55	104.76	29.58	99.40	29.47	99.36	29.2	99.15
	0	160	32.46	104.47	29.6	99.46	29.48	99.39	29.22	99.22
REMARKS			Not Responsive, Reversed and Limited Span (0-2.09 on 500Ω Range)		Narrow Bandwidth only at 5000Ω		Narrow Bandwidth only at 5000Ω		Scaling possible only at 5000Ω	

The expected normal behaviour on an input resistance range of 500 ohms is illustrated in figure 10 as produced in the software virtual simulation.

It can be noted from figures 8 to 9 that for U3, U4, U5 the current rises steadily up to 100% at 50 ohms input resistance and then saturates steadily to 160 ohms value that was used. This is about 31.25% of the total input resistance required to produce corresponding current output. This looks like the current output characteristics of an independent voltage source where the current remains constant after the initial internal resistance of the source, no matter the connected load.

U2 has a reverse characteristic and when terminals 1 and 11 were swapped it responded as others. This shows an erratic connection to ground of the internal components.

As a result of the above developments, it became obvious that we investigate the type of output coming out in this configuration (voltage or current), so we changed the program output from current to voltage and the corresponding results are shown in table 7 and figure 11 below.

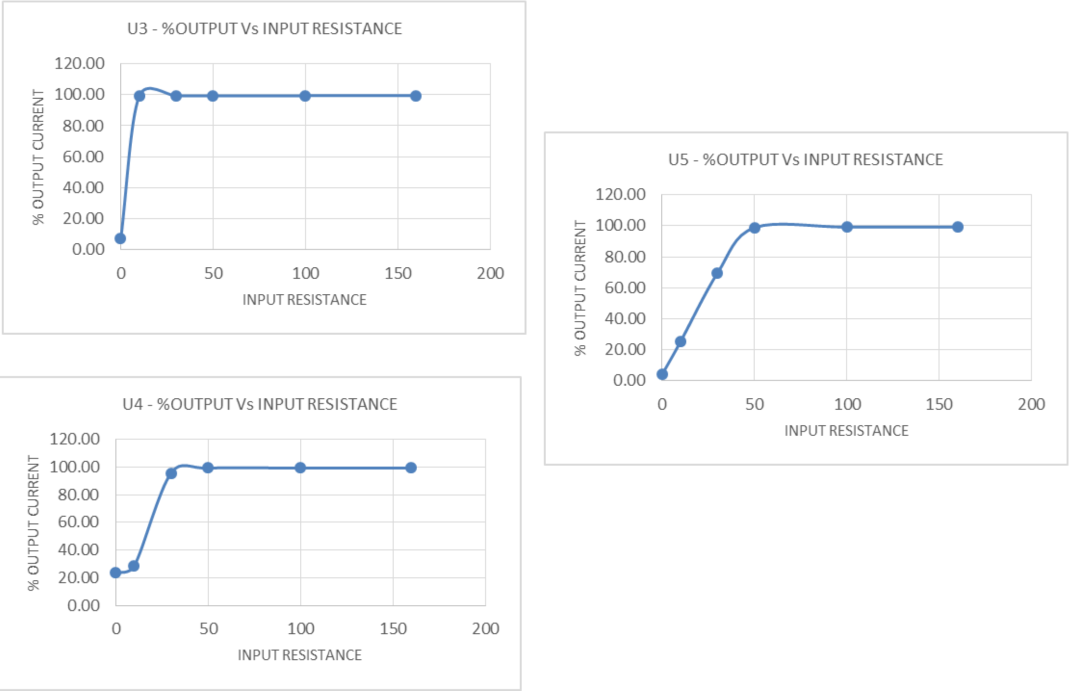
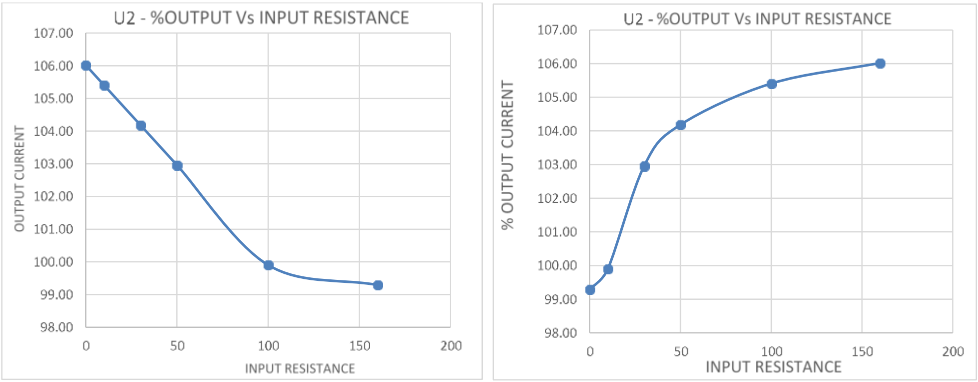


Figure 8: Characteristics of Temperature Transmitter (U3 – U5) before adjustments



9a: U2 Characteristic with normal Input (1,6,11)

9b: U2 Characteristic with reversed Input (11,6,1)

Figure 8: Reversed Characteristics exhibited by U2 before adjustments

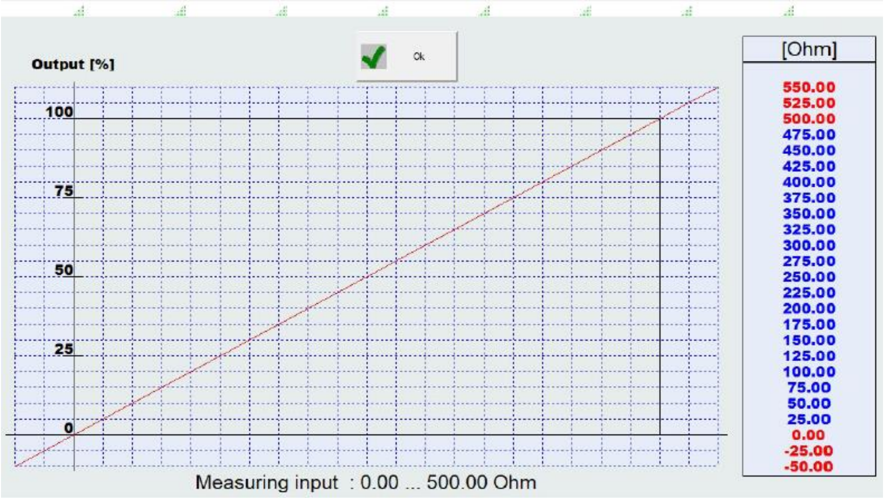


Figure 10: Simulated Temperature Indicator Virtual Output Characteristic

Table 7: Tests on Temperature Transmitter SINEAX 604 using output voltage alternative.

LINEAR 3-WIRE RESISTANCE

MEASURING RANGE (Ω)	MEASURED INPUT (Ω)		TRANSMITTER OUTPUT AT 0 - 10V SETTING (V)							
	TERMINAL 1-6	TERMINAL 6-11	U2		U3		U4		U5	
			VALUE	%	VALUE	%	VALUE	%	VALUE	%
OPEN CIRCUIT	>500	0			14.05	100	13.35	100		
0 – 500	500	0			0	0.00	0	0.00		
	400	150			2.5	17.79	2.43	18.20		
	300	200			5.03	35.80	4.23	31.69		
	200	300			7.57	53.88	7.26	54.38		
	150	400			10.11	71.96	9.7	72.66		
	0	500			12.66	90.11	12.14	90.94		
0 – 740	500	0			0	0.00	0	0.00		
	400	150			1.69	12.03	1.63	12.21		
	300	200			3.43	24.41	3.28	24.57		
	200	300			5.15	36.65	4.35	32.58		
	150	400			6.28	44.70	6.61	49.51		
	0	500			8.6	61.21	8.28	62.02		
0 – 1000	500	0			0	0.00	0	0.00		
	400	150			1.26	8.97	1.21	9.06		
	300	200			2.53	18.01	2.45	18.35		
	200	300			3.23	22.99	3.67	27.49		
	150	400			5.12	36.44	4.31	32.28		
	0	500			6.38	45.41	6.15	46.07		
REMARKS					Good Results. Responded only after Reversal of DIP Switches.		Good Results. Responded only after Reversal of DIP Switches.			

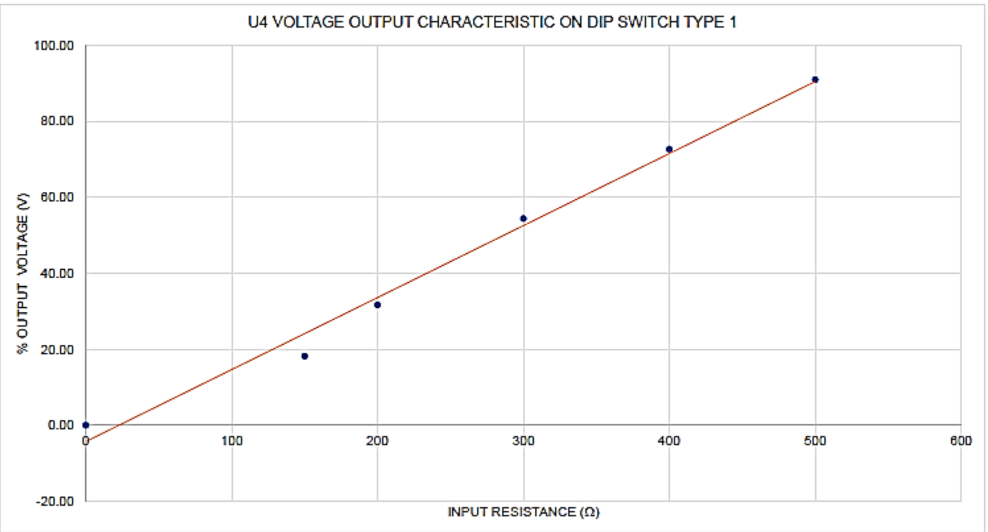


Figure 11: Output Characteristic of SINEAX 604 using voltage alternative on DIP Switch type 1

As a result of this development, we decided to open all the modules, reset the respective DIP Switches and re-program on 500 ohms resistance range since the inputs on the field is a maximum of 400 ohms as indicated on table 5 above. The respective results are tabulated in table 8 below.

Table 8: Test Reports on Temperature Transmitter SINEAX 604 after adjustments

LINEAR 3-WIRE RESISTANCE

MEASURING RANGE (Ω)	MEASURED INPUT (Ω)		TRANSMITTER OUTPUT AT 4 - 20mA SETTING (mA)							
	TERMINAL 1-6	TERMINAL 6-11	U2		U3		U4		U5	
			VALUE	%	VALUE	%	VALUE	%	VALUE	%
OPEN CIRCUIT	>500	0	21.49	100	21.54	100	21.55	100	21.57	100
0 – 500	500	0	5.43	25.27	4.01	18.62	4.02	18.65	4.03	18.68
	400	100	8.2	38.16	7.15	33.19	7.2	33.41	7.22	33.47
	300	200	13.4	62.35	10.39	48.24	10.43	48.40	10.4	48.22
	200	300	15.3	71.20	13.6	63.14	13.68	63.48	13.63	63.19
	100	400	19.56	91.02	16.83	78.13	16.88	78.33	16.82	77.98
	0	500	21.45	99.81	20.54	95.36	20.08	93.18	20.03	92.86
0 – 740	500	0	4.46	20.75	4.02	18.66	4.01	18.61	4.02	18.64
	400	100	6.58	30.62	6.17	28.64	6.16	28.58	6.17	28.60
	300	200	10.26	47.74	8.33	38.67	8.39	38.93	8.33	38.62
	200	300	10.92	50.81	10.45	48.51	10.52	48.82	10.51	48.73
	100	400	13.05	60.73	12.71	59.01	12.68	58.84	12.68	58.79
	0	500	15.25	70.96	14.88	69.08	14.84	68.86	14.85	68.85
0 – 1000	500	0	4.53	21.08	3.95	18.34	4.01	18.61	4.02	18.64
	400	100	6.43	29.92	5.65	26.23	5.62	26.08	6.18	28.65
	300	200	7.94	36.95	7.2	33.43	7.25	33.64	8.33	38.62
	200	300	9.92	46.16	8.8	40.85	8.83	40.97	10.51	48.73
	100	400	11.16	51.93	10.42	48.38	10.43	48.40	12.68	58.79
	0	500	12.76	59.38	12.02	55.80	12.03	55.82	14.83	68.75
REMARKS			Responded only after Reversal of DIP Switches and interchange of terminals 1 and 11		Good Results. Responded only after Reversal of DIP Switches.		Good Results. Responded only after Reversal of DIP Switches.		Good Results. Responded only after Reversal of DIP Switches.	

The corresponding characteristic curves for each transducer at 500 ohms range and 4 – 20mA output are given in figures 12 – 15 below:

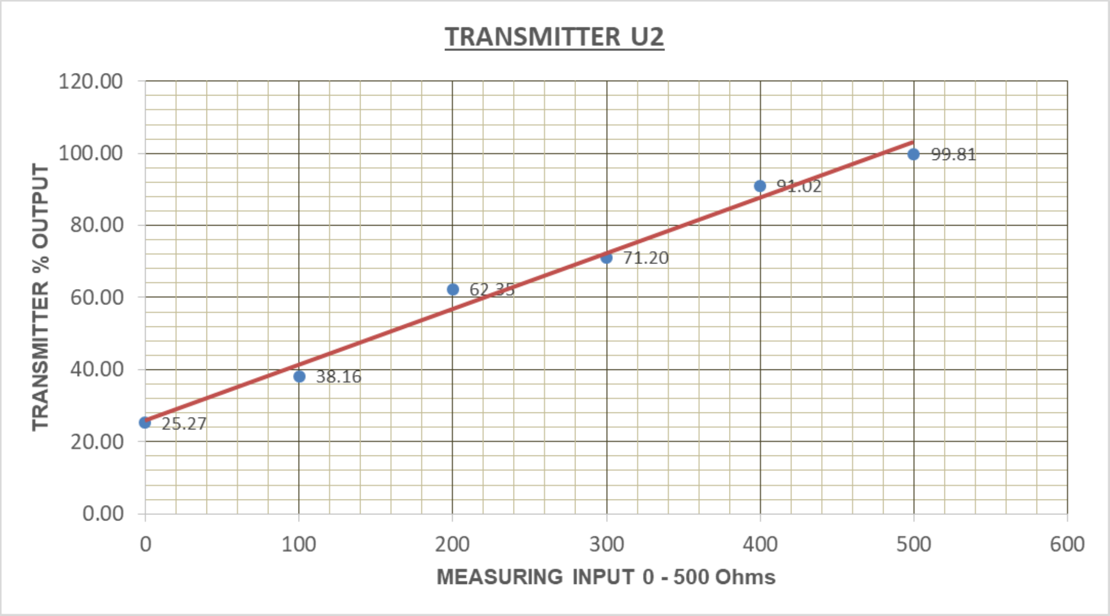


Figure 12: Output Characteristic of SINEAX 604 (U2) on DIP Switch type 2

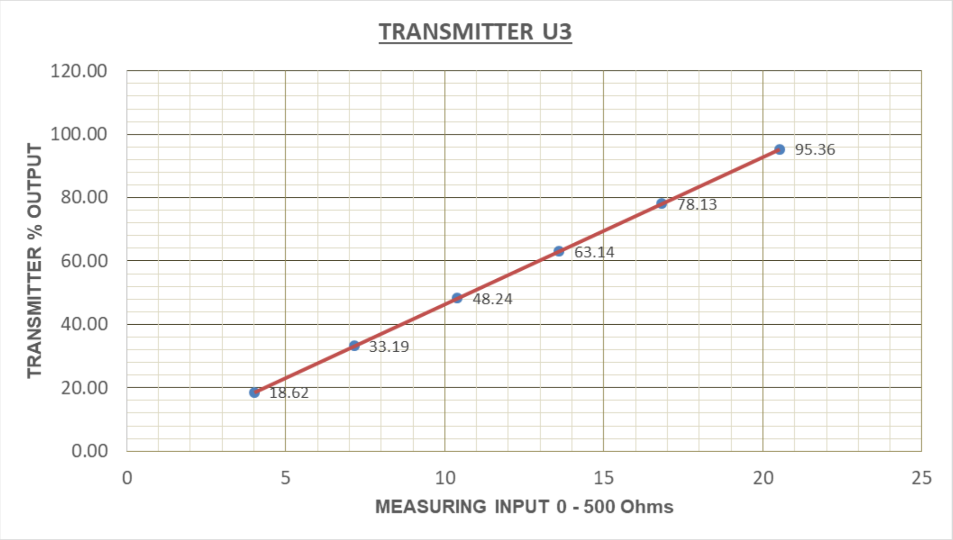


Figure 13: Output Characteristic of SINEAX 604 (U3) on DIP Switch type 2

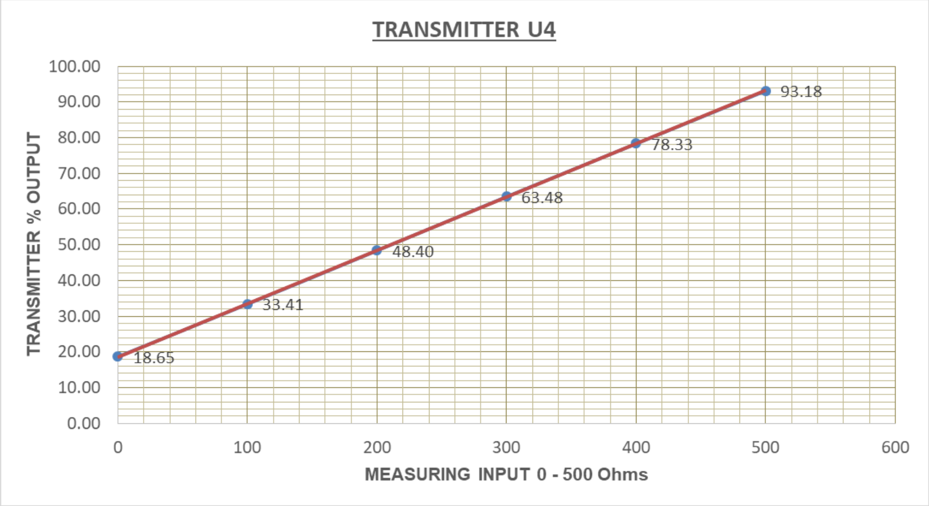


Figure 14: Output Characteristic of SINEAX 604 (U4) on DIP Switch type 2

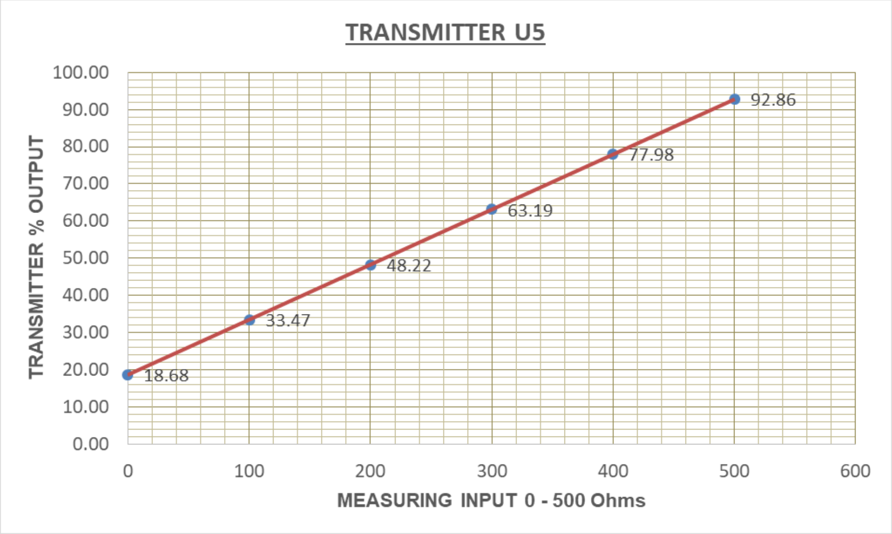


Figure 15: Output Characteristic of SINEAX 604 (U5) on DIP Switch type 2

Technical Notes:

It must be noted here that inputs to two (2) out of the four transducers are having some issues from the thermometer end of the potentiometer as follows:

1. Potentiometric Input from Oil/Winding Temperature Indicator on the transformer tied to U5 was open-circuited for temperatures above 30^{0}C and so will indicate maximum value for any other temperature above this range. This is because the lower end of potentiometer is broken as shown in figure 16 below and required a major repair/replacement.

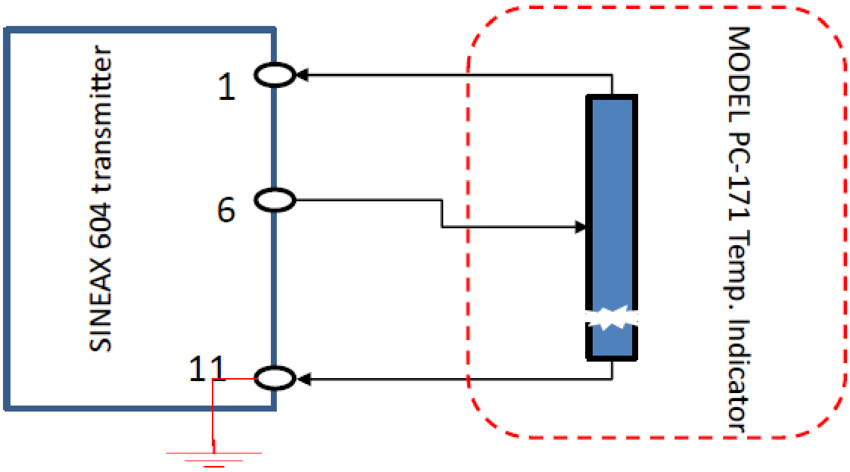


Figure 16: Illustration of Potentiometer Broken link on temperature Indicator

2. There was partial contact on the Temperature indicator tied to transducer U3/U4 due to noticeable dirt films on the potentiometer-slider contact. This was cleaned up to prevent erratic behaviour of transmitter output. See illustration below (fig. 17).

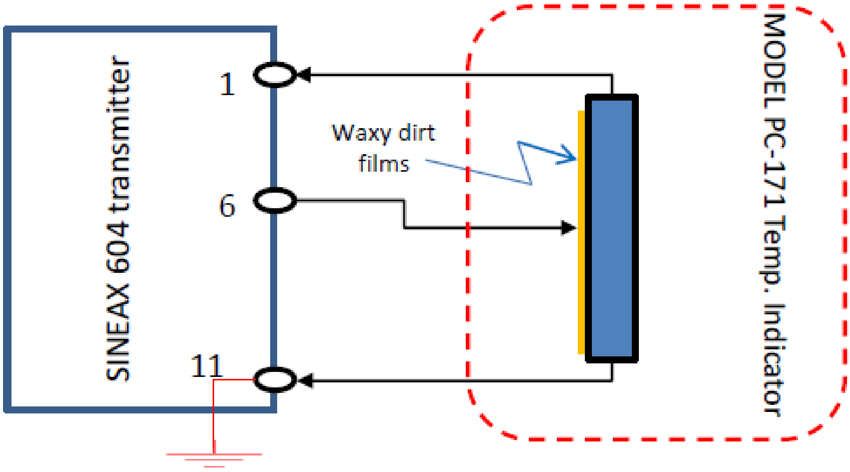
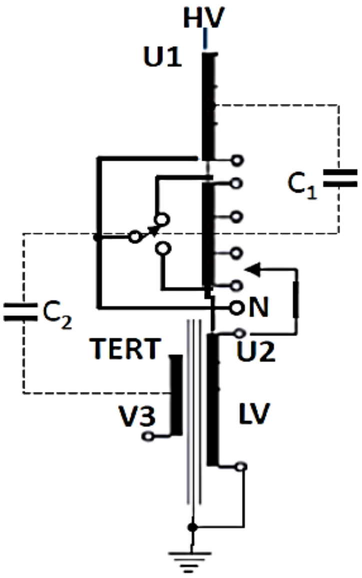


Figure 17: Illustration of Potentiometer Partial Contact

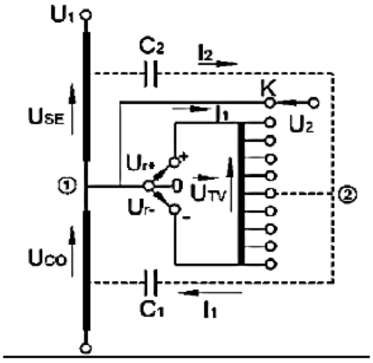
VI. Performance Evaluation And Discussions

Transformer Health Monitoring involves temperature monitoring and control for oil-filled transmission and distribution transformers. To ensure the correct operation of the Field Controller and Remote Regulator/Position indicator (PI), several parameters must be settled in the two, which will provide the equipment the necessary information for its operation. Accurate position communication with the local Universal Transmitter is critical to the entire system operation.

The tap winding is galvanically isolated from the main winding by the change-over selector during the transition from the "+" contact to the "–" contact, when the tap winding is electrically floating, and a recovery voltage V_{R+} exists between the stationary contact (+) and Tap_A0 resulting from the potential of the adjacent windings and winding coupling capacitances as well as V_{R-} when change-over selector switches from "-" to the "+"contact. A typical analysis with the Auto-transformer under consideration is laid out in figure 18 below.



**HV REGULATED
REVERSING
AUTO-TRANSFORMER**



**LV REGULATED
REVERSING
AUTO-TRANSFORMER**

An auto-transformer has two windings and they are the high voltage (HV) - and the low voltage (LV) - winding. In some instructions and manuals the HV winding is called series winding and the LV winding is called common winding.

1 The recovery voltages and switch currents can be calculated by using the equivalent circuit shown in the first Figure.

2 The voltage V_{X1} represents the voltage (w.r.t. ground) of the change-over selector contact "0", which is connected to the end of the HV winding.

3 U_{RW} is the voltage across the tap winding

Calculations - HV regulated

From the Figure assuming that winding capacities C1 and C2 are effective in the middle of the winding;

Note:

$HV/LV = U_1/U_2$

Step voltage is calculated by following formula:

$$U_{STEP} = \frac{U_{1r.s.}}{\sqrt{3}} = \frac{U_{TAP.}}{2} = \frac{U_T}{\sqrt{3}} = U_{RW} = \frac{U_{system.r.r}}{\sqrt{3}}$$

The voltage over each step in the regulating winding calculated by taking the phase voltage times the step (%).

Voltage at the line end: $= \frac{U_{system}}{\sqrt{3}}$; Neutral end: $V_s = 0$ kV; In the middle of the winding: $= \frac{U_{system}}{2\sqrt{3}}$

The potential (V_S) at the change-over selector is:

$$\therefore V_S = \frac{U_2}{\sqrt{3}} \text{ (HV Regulated) OR } V_S = 0 \text{ (LV Regulated)}$$

The potential for each winding:

$$V_1 = \frac{U1 - U2}{2\sqrt{3}} + \frac{U2}{\sqrt{3}}; \qquad V_3 = \frac{U2}{2\sqrt{3}}$$

U_3 = Tertiary winding or Tank.

$$V_{X1} = (V1 - V3)\frac{C1}{C1+C2} + V_3$$

Recovery voltages:

$$U_{R\pm} = V_S - V_{X1} \pm \frac{U_{RW}}{2}, = \frac{U_2}{\sqrt{3}} - ((V1 - V3)\frac{C1}{C1+C2} + V3) \pm \frac{U_T}{2\sqrt{3}}$$

$$\Rightarrow U_{R\pm} = \frac{U_2}{\sqrt{3}} - ((\frac{U1 - U2}{2\sqrt{3}} + \frac{U2}{\sqrt{3}} - \frac{U2}{2\sqrt{3}})\frac{C1}{C1+C2} + \frac{U2}{2\sqrt{3}}) \pm \frac{U_T}{2\sqrt{3}}$$

$$U_{R\pm} = \frac{U_2}{2\sqrt{3}} - (\frac{U1}{2\sqrt{3}})\left[\frac{C1}{C1+C2}\right] \pm \frac{U_T}{2\sqrt{3}}; \qquad \text{(HV Regulated)}$$

$$= -\frac{U_2}{2\sqrt{3}} + (\frac{U1}{2\sqrt{3}})\left[\frac{C2}{C1+C2}\right] \pm \frac{U_T}{2\sqrt{3}} \qquad \text{(LV Regulated)}$$

$$|I_{R\pm}| = U_{R\pm} \cdot j\omega\,(C1 + C2)$$

$$|I_{R\pm}| = \omega\left[\frac{U2}{2\sqrt{3}}(C1 + C2) \pm \frac{U_T}{2\sqrt{3}}(C1 + C2) - \frac{U1}{2\sqrt{3}}C1\right]$$

Figure 18: Breaking strength calculation of change-over selector contacts for Auto-transformer.

A voltage regulator controller equipped with multiple control programs, operates in such a way that at any given time, one of the control programs is selected to be "active" depending on the existing operating conditions. An operator (user) configures the voltage regulator control to change its active control program based on a number of factors, which can include, for example, demand metering values, the time and/or date, external inputs such as the measured transformer oil temperature, commands received via a serial communications port and fault/maintenance status. A major component of Voltage and Power Control system in a transformer assembly is the On-load Tap-changer (OLTC). The purpose of a tap changer is to regulate the output voltage of a transformer by altering the number of turns in one winding and thus changing the turns ratio of the transformer.

Many power transformer failures are due to On Load Tap-changer (OLTC) problems. Tap changing causes change in leakage reactance, core loss, and copper loss. A healthy OLTC generates very little heat when it is not switching, so the temperature of the OLTC tank is typically lower than the main tank. When the transformer and OLTC are operating normally, the long-term temperature differential between the two tanks is roughly constant. As the OLTC switch contacts age or wear, their resistance increases. The **breaking currents** are increased due to the extra current going through the tie-in resistor. There is, therefore a relationship between the tap-changer, transformer temperature Rise, and load. This relationship is amplified when the transformer is either aging or operates wrongly due to malfunction of controllers. This relationship is defined by some form of analysis.

The Nameplate information of the transformer in question as well as the vector configuration are shown in figure 19. The illustration of coupling Capacitance at the point of transition is shown in figure 20. It shows an autotransformer where the regulating winding couples to a delta-connected tertiary winding. Different winding geometries are used in actual evaluation process, some of them require consideration of a third or fourth capacitance.

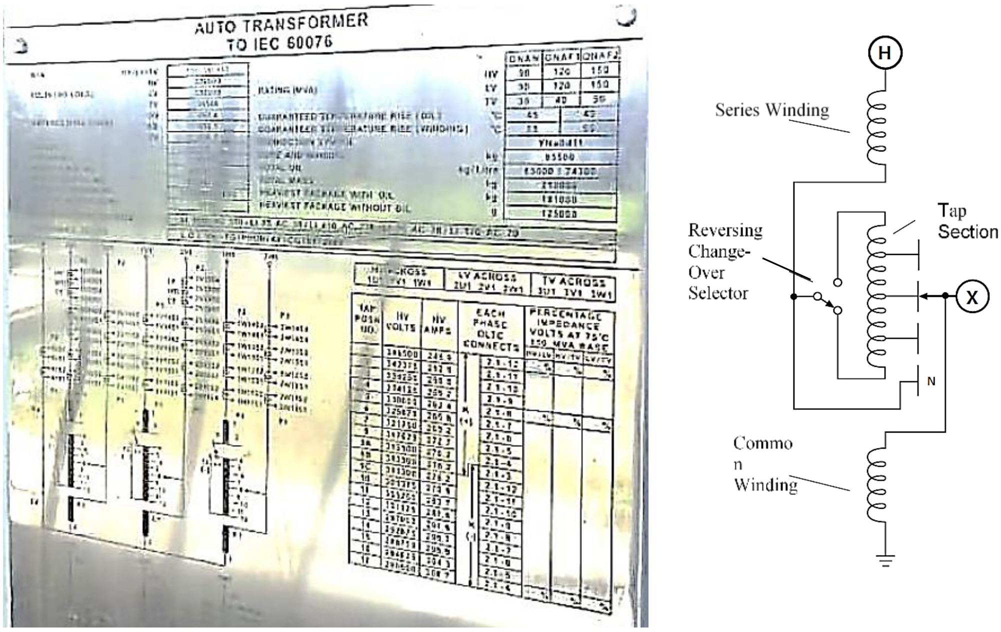


Figure 19 – Transformer Nameplate and the Autotransformer Winding Configuration per Phase

The transformer particulars are as follows:

MVA(HV/LV/TV) – 150/150/50 **VOLTS (NO – LOAD)** - HV – 330000 LV – 132000 TV – 34500 **AMPERES(F.LOAD)** HV – 262.4 LV – 656.1 TV – 836.7	PHASES – 3 FREQUENCY – 50Hz PERCENT IMPEDANCE: TAP 1 – 11.4%(HV/LV), 28.76%(HV/TV). TAP 9 – 11.2%(HV/LV), 29.02(HV/TV), 13.46%(LV/TV) TAP 17 – 13.5%(HV/LV), 30.3%(HV/TV) 2

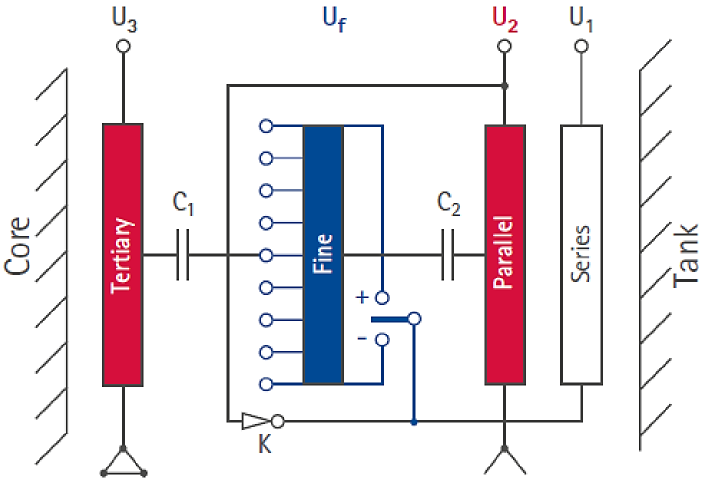
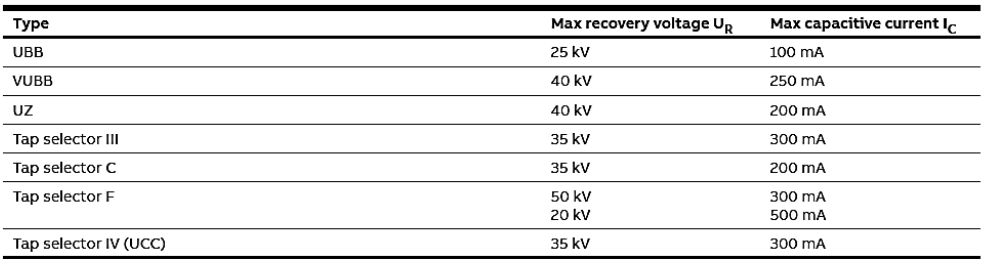


Figure 20 – Illustration of Capacitor Coupling for Autotransformer, regulating winding coupled to tertiary winding (Source: Rainer Frotscher [17])

The required switching capacity (the product of switched current and recovery voltage) for a specific contact in an OLTC is based on the relevant step voltage and current. A small capacitive current in the order of tens of milliamps is switched at a recovery voltage of tens of kilovolts. After transferring the current, the gap between the contacts stressed during the change-over must be capable of withstanding the recovery voltage and switch currents.

Typically allowed values for ABB Transformers are stated in the technical guides for each tap-changer as indicated on table 9 below:

Table 9: Typical Values of Permissible Breaking Strength for ABB Tap-changers



Type	Max recovery voltage U_R	Max capacitive current I_C
UBB	25 kV	100 mA
VUBB	40 kV	250 mA
UZ	40 kV	200 mA
Tap selector III	35 kV	300 mA
Tap selector C	35 kV	200 mA
Tap selector F	50 kV 20 kV	300 mA 500 mA
Tap selector IV (UCC)	35 kV	300 mA

UBB	Specified for cover-mounting or for yoke-mounting inside transformer, with separate tank and oil-immersed.	Tap Selector C (VUCG)	The VUC range of tap-changer made up of two diverter switches in vacuum interrupters and three tap selectors. Load Current continuous through the vacuum interrupters.
VUBB	Specified for cover-mounting or for yoke-mounting inside transformer, with separate tank with vacuum interrupters.	Tap Selector F(50): (VUCG, VUCL diverter switches) Tap Selector F(20)): (VUCG, VUCL diverter switches)	The VUC range of tap-changers made up of two diverter switches in vacuum interrupters and three tap selectors. Load Current continuous through the vacuum interrupters (VUCG) or by-pass contact for the load current (VUCL).
UZ	Separate Tank, Oil-immersed combined tap selector and diverter switch	Tap Selector IV (UCC)	Spring-operated diverter switch and the tap selector with sliding contacts. Non- vacuum interrupters diverter switches.
Tap Selector III: (VUCG, VUCL diverter switches)	The VUC range of tap-changers made up of two diverter switches in vacuum interrupters and three tap selectors. Load Current continuous through the vacuum interrupters (VUCG) or by-pass contact for the load current (VUCL).		

At the moment of transition, when the regulating winding is galvanically disconnected from the main winding the contacts of the change-over selector can be exposed to high capacitively divided voltage. The tap winding takes a new potential which is determined together by the coupling capacitance to ground C_E and coupling capacitance to the adjacent winding C_W This bias voltage turns is the recovery voltage U_W on the gap of the change-over selector and when it exceeds a certain critical value, the change-over selector would discharge electricity with a considerable current called breaking current I_S.

To investigate the possible impact of Controller mal-operation, we shall illustrate with an example using capacitor coupling illustration in figures 21, 22 and realistic values of tables 10 and 11 below.

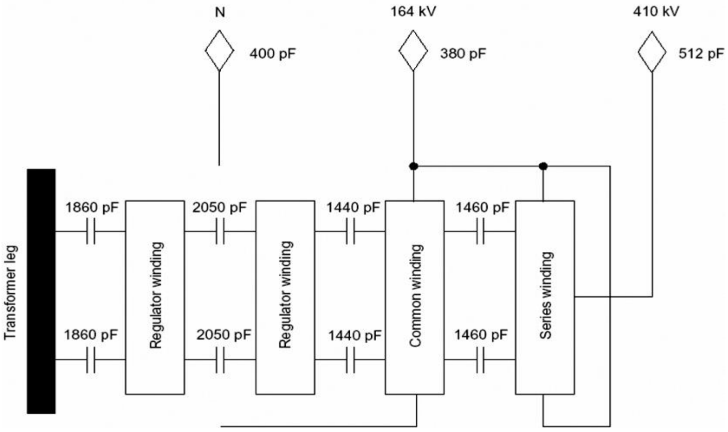


Figure 21: Typical Capacitance values for the autotransformer windings (ABB)

This is represented by one-phase of a three-phase Saturable Transformer Component (STC) Model of the Auto-transformer in figure 22 below, showing Series (S), Common (C) and Tertiary (T) Winding integral components.

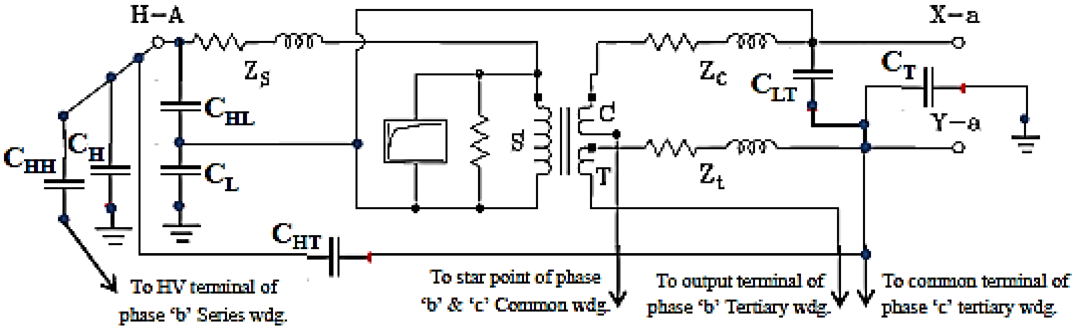


Figure 22: STC Model for Phase 'A' of a Three-phase Three-winding Autotransformer

The capacitances represent the electric coupling between two windings of the same phase or between each winding and the earthed fittings of the transformer, i.e. the tank and the core or tertiary winding. The effective terminal capacitance can be determined based on the frequency of oscillation of each winding by using Equations (1) through (5)

$$\text{Effective capacitance } C_{eff} = 1/[(2\pi f)^2 \cdot L] \qquad (1)$$

where f: TRV frequency of each winding in Hz,
L: transformer leakage inductance in H, C_{eff}: effective capacitance in F
Effective capacitance for the high-voltage winding $C_{eff} = C_H + C_{HL}$ (2)
Effective capacitance for the low-voltage winding $C_{eff} = C_L + C_{HL}$ (3)
Effective capacitance for tertiary winding $C_{eff} = C_T + C_{HL} + C_{LT}$ (4)
High-frequency capacitive coupling ratio $C_{HL}/(C_{HL}+C_L)$ (5)

Table 10: Typical Effective Capacitance Range from Table B.9 of ANSI/IEEE C37.011-1994 [35]

Transformer Size (MVA)	Voltage (kV)	Effective Capacitance (pF)
1~ 10	15 kV ~121 kV	900~10,000
10~100	15 kV ~121 kV	2000~12,000
	121 kV ~550 kV	2000~6500
100~1000	121 kV ~550 kV	3500~16,000

Table 11: Selected Winding Capacitances for a 345/118/13.8kV Example Transformer [35]

C_{HL}	C_L	C_H	C_{HT}	C_T	C_{LT}
3,027 pF	*7,063 pF*	*2,266 pF*	*574 pF*	*10,336 pF*	*681 pF*

Example of recovery voltage calculation:
Auto-transformer connected and regulated at mid-point.
Rated capacity: PN = 150MVA
HV winding: 330kV (1±10×1.25%), Common Winding (U2) =
LV winding: 132kV
Winding capacitance: C_1 = 2266pF (between main winding and tap winding)
C_2 = 574pF (between tap winding and earth)
Assume winding capacitance C_1 and C_2 is concentrated on mid of winding, by above data:
U_1 = 330kV; U_T = 330×12.5% = 41.25kV (transition voltage)

$$\therefore |U_{r+}| = \frac{U_2}{2\sqrt{3}} - \left(\frac{U1}{2\sqrt{3}}\right)\left[\frac{C1}{C1+C2}\right] + \frac{U_T}{2\sqrt{3}} = -132/2\sqrt{3} + (330/2\sqrt{3})\ x\ [\frac{2266}{2266+574}] + 41.25/2\sqrt{3}) = \mathbf{49.81}\boldsymbol{kV}$$

$$|U_{r-}| = \frac{U_2}{2\sqrt{3}} - \left(\frac{U1}{2\sqrt{3}}\right)\left[\frac{C1}{C1+C2}\right] - \frac{U_T}{2\sqrt{3}} = -132/2\sqrt{3} + (330/2\sqrt{3})\ x\ [\frac{2266}{2266+574}] - 41.25/2\sqrt{3}) = \mathbf{25.99}\boldsymbol{kV}$$

$$|I_{s+}| = \omega\left[\frac{U1}{2\sqrt{3}}C1 \pm \frac{U_T}{2\sqrt{3}}(C1+C2) - \frac{U2}{2\sqrt{3}}(C1+C2)\right] = 2\pi x50\left[\left(\frac{330}{2\sqrt{3}}\right)x2266 + \left(\left(\left(\frac{41.25}{2\sqrt{3}}\right) - \left(\frac{132}{2\sqrt{3}}\right)\right)x(2266 + 574)\right)\right]10^{-9}$$

$$= \mathbf{443.78mA}$$

$$|I_{s-}| = \omega\left[\frac{U1}{2\sqrt{3}}C1 \pm \frac{U_T}{2\sqrt{3}}(C1+C2) - \frac{U2}{2\sqrt{3}}(C1+C2)\right] = 2\pi x50\left[\left(\frac{330}{2\sqrt{3}}\right)x2266 - \left(\left(\left(\frac{41.25}{2\sqrt{3}}\right) - \left(\frac{132}{2\sqrt{3}}\right)\right)x(2266 + 574)\right)\right]10^{-9}$$

$$= \mathbf{912.54mA}$$

It must be noted that there are several factors that may result to creation of additional parallel Parasitic Capacitances and leakage current resulting from unstable tap-changing operation due to controller mal-operation and ERRATIC SWINGS.

Assuming the Capacitance is doubled in the course of the erratic operation of the controller, new values are obtained for the system under consideration as follows:

Winding capacitance: $C_1 = 4532pF$ (between main winding and tap winding)

$C_2 = 1148pF$ (between tap winding and earth)

$$\therefore |U_{r+}| = \frac{U_2}{2\sqrt{3}} - \left(\frac{U1}{2\sqrt{3}}\right)\left[\frac{C1}{C1+C2}\right] + \frac{U_T}{2\sqrt{3}} = -\ 132/2\sqrt{3} + (330/2\sqrt{3})\ x\ \left[\frac{4532}{4532+1148}\right] + 41.25/2\sqrt{3}) = \mathbf{49.81\boldsymbol{kV}}$$

$$|U_{r-}| = \frac{U_2}{2\sqrt{3}} - \left(\frac{U1}{2\sqrt{3}}\right)\left[\frac{C1}{C1+C2}\right] - \frac{U_T}{2\sqrt{3}} = -\ 132/2\sqrt{3} + (330/2\sqrt{3})\ x\ \left[\frac{4532}{4532+1148}\right] - 41.25/2\sqrt{3}) = \mathbf{25.99\boldsymbol{kV}}$$

$$|I_{s-}| = \omega\left[\frac{U1}{2\sqrt{3}}C1 \pm \frac{U_T}{2\sqrt{3}}(C1+C2) - \frac{U2}{2\sqrt{3}}(C1+C2)\right] = 2\pi x50\left[\left(\frac{330}{2\sqrt{3}}\right)x4532 + \left(\left(\left(\frac{41.25}{2\sqrt{3}}\right) - \left(\frac{132}{2\sqrt{3}}\right)\right)x(4532 + 1148)\right)\right]10^{-9}$$

$$= \mathbf{888.854mA}$$

$$|I_{s-}| = \omega\left[\frac{U1}{2\sqrt{3}}C1 \pm \frac{U_T}{2\sqrt{3}}(C1+C2) - \frac{U2}{2\sqrt{3}}(C1+C2)\right] = 2\pi x50\left[\left(\frac{330}{2\sqrt{3}}\right)x4532 - \left(\left(\left(\frac{41.25}{2\sqrt{3}}\right) - \left(\frac{132}{2\sqrt{3}}\right)\right)x(4532 + 1148)\right)\right]10^{-9}$$

$$= \mathbf{1823.80mA} = \mathbf{1.824A}$$

We can see from above analysis that while the Recovery Voltage remains unchanged for both substantive and the successive adjacent tap windings, The Circulating Current is increased by is increased in equal proportion (100)% to capacitance variation. The **constant voltage** may be as a result of the configuration of the autotransformer in form of Capacitive Voltage Transformer at the high voltage and mid-tap/Tertiary windings with a constant capacitor ratio irrespective of capacitance value as against **variable current flow** determined by the Electric Field intensity dependent on tap changer relative geometric transition process.

It is obvious that the recovery voltages U_R+, U_R- for autotransformer cannot be reduced with a large capacitance between the end of the main winding and the center of the regulating winding. Therefore, the important balance between low recovery voltages Uw+, Uw- (which means a large capacitance C1) and low switched currents Is+, Is- (which requires small capacitances), a measure mainly used in phase-shifting transformers is can be achievable with autotransformers in making sure that ridiculous out-of-balance coupling capacitance sizing does not exist.

This can be attributed to the following system phenomena:

(a) **Back to back switching** a specific operation which combines an inrush current during a making process and a power frequency current interruption followed by a subsequent DC recovery voltage during a breaking process,

(b) **Outrush current transient** produced by the Capacitance when the tap changer is operating to connect/disconnect the tap selector switch in process of Transient Recovery Voltage (TRV),

(c) **Secondary resonance** which arises when the liberation frequency of a primary resonance is commensurate with the circulation frequency of a nearby primary resonance and behaves like a simple "perturbed-pendulum".

(d) **Transient Recovery Voltage (TRV)** is the temporary power frequency voltage that occurs between the moving and the fixed contact during change-over selector operation after extinction of the electric arc when the moving contact is temporarily in the intermediate open position.

The procedure for calculating the self-capacitance of high-voltage transformers and identifies all the factors that dictate the electrostatic behavior of these components, and where the switching frequency can rise up to 500 kHz, the parasitic parameters, in particular the self-capacitance, can heavily affect the performance of the transformer. This capacitance is responsible for unwanted resonances and oscillations of the primary and secondary side currents, hence reducing the system's efficiency and reliability. **Detailed Evaluation of these components is beyond the scope of this write-up**.

All other factors being equal, closer plate spacing gives greater capacitance and closer spacing results in a greater field force (voltage across the capacitor divided by the distance between the plates), which results in a greater field flux (charge collected on the plates) for any given voltage applied across the plates. Higher frequency of switching operation gives impression of a continuously closed gap and regenerates higher capacitance values leading to higher current at a fixed recovery voltage.

EFFECT OF CONTROLLER OPERATIONS

Almost all OLTC controls receive input signals scaled to 120Vac and 0.2 Amp for the load voltage and current. The analog circuitry of the traditional control would manipulate those sensed quantities with particular operator selected set points to determine the need for a raise (or lower) tap-change operation to hold the output voltage within the desired band. The circuit of Figure 23 describes this most fundamental scheme.

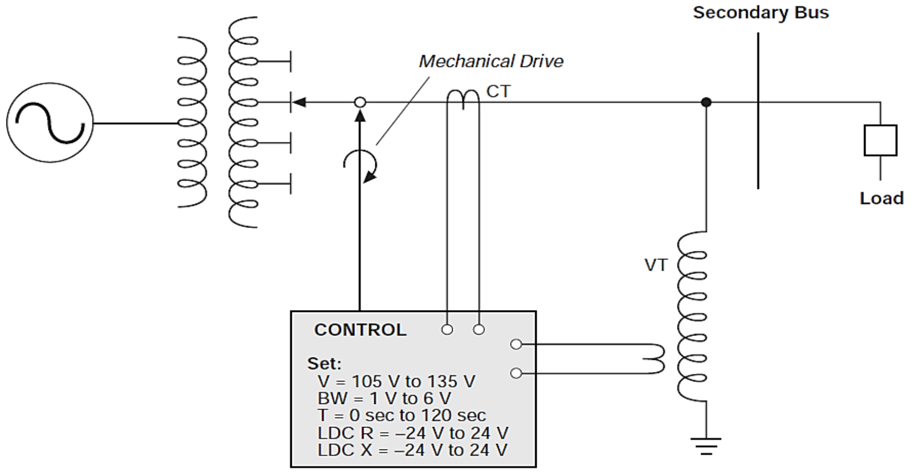


Figure 23 – OLTC Control Circuit Required to Satisfy Basic Criteria [14]

On-load Tap-changing transformers will vary significantly in their degree of complexity. The results of power transformer technical state determination may be used to define its current loading ability. The set of energy system states and processes, the transition from one state into another have their mode characterized by the electrical parameters, such as voltages and substations loading, current in the transmission lines, transformation ratio of the transformers etc. As a result of complexity of conditions that may arise, the possibility of the analysis of control actions of separate OLTC on **mode parameters** of Engineering Equation Solver (EES) may be employed by means of the feedback [29].

Voltage is to be regulated in this case at about the range of 89.5% to 110.5% of the voltage at the input (280.5 – 346.5kV). This regulation is accomplished in 17 discrete steps, so that each step represents:

$$\frac{21\%\ \text{voltage total range of regulation}}{17\ \text{steps}} = 1.235\%\ \text{voltage / step}$$

Since this controller senses the output of a 110 Vac potential device, a one-step change of the OLTC, results in a voltage change of 1.3585 V at the control potential input. **Any variation from the field sensor can totally disrupt the entire operation.** The real objective of tap-changing is to hold the voltage at the load to a desired level. To accomplish this, controls include a provision to set **Line Drop Compensation** (LDC). This provides the control with the additional feature of modeling the impedance of the distribution feeder between the LTC and the load, to compensate for the voltage drop of the feeder as shown in figure 24.

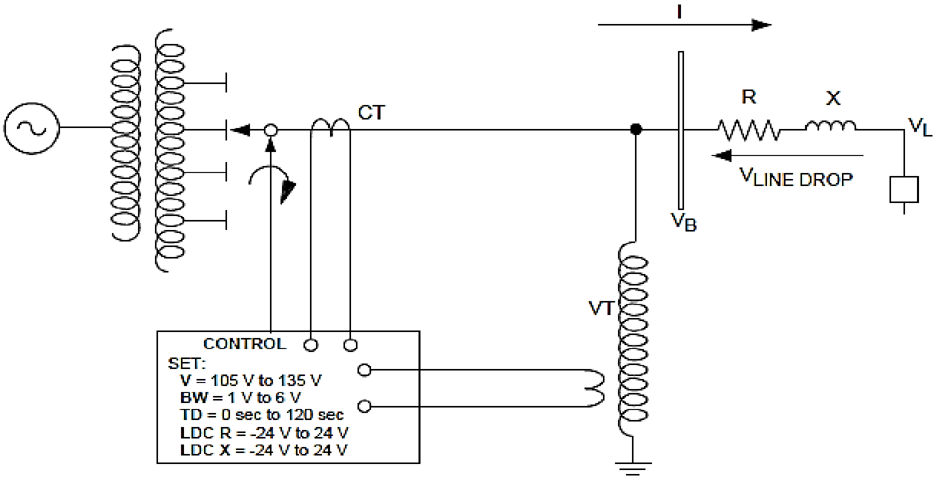


Figure 24 – OLTC Control Circuit Required to Satisfy Voltage Stability Objective [14]

Lacking a means of remote communications as in traditional control concept deployed here, the control has no way to directly know V_L at the end of the line. Therefore, as seen in Figure 25, three values allow the control to model (or calculate) V_L.

1. The bus voltage VB
2. The feeder current I
3. The feeder resistance R and reactance X

Therefore, with knowledge of the three values above, the control can be programmed to adjust the bus voltage (V_B) to compensate for the voltage drop in the feeder line between the bus and the load. As illustrated in Figure 24 below, when proper phasor relationships are considered, it is evident that:

$$\vec{V}_L = \vec{V}_B - \vec{V}_{LINE\ DROP}$$

$$\vec{V}_L = \vec{V}_B - \vec{I}\,(R + jX)$$

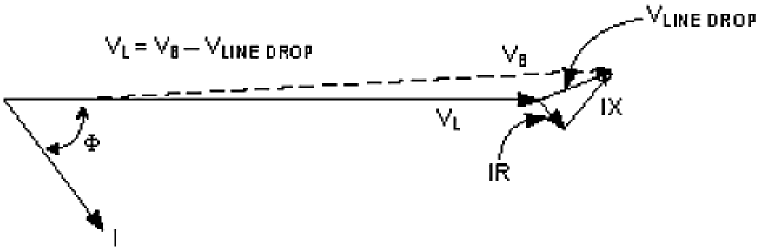


Figure 25 – OLTC Control Circuit Required to Satisfy Voltage Stability Objective

Evidently, the control must resolve the system parameters of V_B, V_L as functions of R, X with phase angle Φ and accomplish the solution as indicated by the previous equations.

To establish proper control settings, the following must be considered:

1. Desired voltage level at the load: the desired voltage level at the load will typically be about 110 V. It is this value which is to be set on the control.
2. Bandwidth – establishing the desired Bus level Objective.
3. Time Delay – establishing the desired Bus level Objective
4. Line Drop Compensation – LDC is set using individual R and X values.

The LDC values are calibrated on the control in volts (not ohms), where the setting is representative of the line drop in volts on a 110 V base, and any deviation in field data will definitely cause mal-operation.

TECHNICAL NOTES:

It must be noted that as a result of the phenomenon described in section 4.0 above, there is bound to be erratic tap-change operation because of the information mismatch between what actually obtains on the field and communication disorder between the Universal Controller on the field and the Intelligent Voltage Regulator in the control room. There is the possibility of unstable tap-changing operation with forward-backward Swing of Contacts. The phenomena of **Back to back switching**, **Outrush current transient**, **Secondary resonance**, and **Transient Recovery Voltage (TRV)** become amplified.

While the actual situation on the field suggests the need to step-up from tap 15 (288.75kV), the Regulator receives information from the Field Controller that there is the need to step down from tap 1 (346.5kV) and instructs the Motor Drive Unit accordingly. In the process, the potentiometric resistor steps attached to the MDU mechanism are re-shuffled and the perpetual cycle continues unabated if not checked. On the other hand, inaccurate information from the field on actual temperature status can spell doom for the transformer.

In the process, two things will happen:

a. The mission of temperature measurement in OLTC to determine the true **temperature differential** between the main and tap-changer tank fluids reject transient temperature differences and alarm or disconnect when the true temperature differential exceeds a pre-set magnitude would be defeated. Temperature mismatch mentioned in section 5.0 above can lead to some disastrous situations if not checked. As the Tap-Changer switch contacts age or wear, their resistance increases, and at some point, the heat becomes too great for the surrounding fluid to dissipate. **Rapid contact degradation and TC failure eventually occur**.
b. Endless arcing on the slider contact and tap positions are enhanced resulting in possible deposit of **film compounds** between the contact and tap positions overtime, leading to **Coking**, a process that typically occurs when there are carbon particles in the insulating fluid that may get trapped between the contacts. As the carbonization increases, the IR heating becomes so severe, the hot metal gases begin to build as the contacts become hotter to a point that the contacts may melt. It may result to deposits of dielectric materials in addition to the Resistive components, giving rise to additional series capacitance with the galvanic components at the fixed and moving contacts. This can alter the values of Recovery Voltage and Switched Currents as well as **Resistive Thermal Effect** significantly.

The tap changer operation is a considerable indicator for the operation of the transformer and that is in the function of the load changes and voltage optimization in the power system, whether in the transmission or distribution system, and one of the factors that affect the longevity and reliability of transformers is the tap changer.

VII. Conclusion:

It is hereby concluded that if electronic field transducer measurements are not properly coordinated with actual physical transformer parameters, a catastrophic failure could result to loss of vital and very costly equipment in the power system. This may lead to a system collapse resulting to an extensive outage and colossal revenue loss.

Compared to the main equipment, cost of installed electronic modules is very insignificant but vital and everything must be put in place to see that accurate measurement is made by the field transducer and reliably communicated to the control room.

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