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Comparative Evaluation of Shutdown Resistance Variation Approximation Curves for Temperature-Rise Testing of Distribution Transformers Aimed at Determining Appropriate Curve Type

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ABSTRACT: Transformers play a vital role in power transmission and distribution systems, contributing not only to energy transfer but also to broader economic growth, industrial development, and technological progress. When a transformer fails, it leads to financial setbacks and disrupts the dependable delivery of electricity to consumers.

In oil-filled transformers, the insulating oil functions as both an electrical insulator and a cooling agent. The cooling system directly influences how much the temperature of the windings and oil can rise under full-load operation. To verify that these temperature limits are not exceeded, temperature rise tests are conducted. A key factor in this process is accurately estimating the winding resistance at the moment of shutdown after the test, as it directly affects the calculation of temperature rise of HV & LV windings.

This study investigates the precision of various approximating curves for estimating resistance variation & shutdown resistance, with the aim of showing how comparative analysis of various approximating curves is necessary for improving the accuracy of winding temperature rise estimation.

KEYWORDS: Distribution transformers, shutdown resistance, linear, quadratic, cubic, exponential, root mean square error.

I. INTRODUCTION

Accuracy of measurement plays a crucial role in testing, as it directly influences the reliability and validity of the results obtained. Precise measurements ensure that the performance and behavior of a system are evaluated correctly, allowing engineers and researchers to make informed decisions. Even small errors or inaccuracies can lead to incorrect conclusions, potentially resulting in equipment failure, safety risks, or inefficient operation. In temperature rise testing of transformers accurate measurement of parameters such as temperature, resistance, etc. is essential to verify compliance with standards and operational limits. Therefore, the use of well-calibrated instruments, proper testing procedures, and careful data recording is vital to achieving dependable and consistent outcomes.

Improving upon testing method accuracy in resistance prediction in temperature rise test is beneficial in the following ways:

- Ensures **reliable and consistent test results**, reducing uncertainty in final temperature rise value.
- Improves temperature rise result **compliance with standards and specifications**.
- Reduces **rework and retesting**, saving time and resources.
- Increases **process's reliability** through accurate performance evaluation



II. TESTS CONDUCTED ON TRANSFORMERS

As per IS 1180 (Part 1:2014) [1], the tests on distribution transformers are broadly classified into routine tests, type tests, and special tests, based on their purpose and frequency of performance.

Routine transformer tests ensure each unit meets electrical and mechanical standards. These include checking winding resistance, verifying voltage ratio, polarity, and phase displacement, and measuring no-load and load losses to assess core and copper losses. Insulation resistance and dielectric tests confirm insulation strength under normal and overvoltage conditions. Finally, mechanical checks like pressure and oil leakage tests ensure the transformer's structural integrity.

Type tests on a transformer prototype or sample validate its design and performance. They include the temperature rise test (checks thermal limits under full load), lightning impulse test (verifies insulation against surges), and short-circuit withstand test (ensures it can handle fault currents). These tests are performed during initial design approval or after major design changes.

Special tests are optional and performed only if requested by the purchaser or specified in the contract. They provide extra assurance of performance or quality and can include noise level measurement, no-load current testing at higher voltages, paint adhesion checks, and oil quality assessments (e.g., breakdown voltage and moisture content) to ensure reliability.

III. TEMPERATURE RISE TEST

A. Method

A temperature rise test [2] is performed to evaluate the condition and performance of transformer windings, as well as cooling components such as radiators and the tank, under full-load conditions similar to actual operation.

The procedure is typically carried out as follows: -

- i). Measure the winding resistance of both the high-voltage (HV) and low-voltage (LV) sides at ambient temperature.
- ii). Determine the load losses and no-load losses under the same ambient conditions.
Convert these losses to a reference temperature of 75 °C.
- iii). Apply the total losses (calculated at 75 °C) continuously to the transformer, and record temperatures at various locations at 1-hour intervals using a temperature scanner until thermal stabilization is achieved (i.e., variation within 1 °C for three consecutive readings over three hours).
- iv). After stabilization, supply the transformer with rated current for one additional hour.
- v). At the end of this period, measure the hot resistance by disconnecting the supply and taking resistance readings at short, regular intervals (e.g., every 30 seconds), and extrapolate these values to estimate the resistance at the moment of shutdown.

After extrapolating resistance curves to get hot resistance R_h final hot winding temperature θ_h can be measured as follows:

$$\theta_h = \frac{R_h \times (225 + \theta_c)}{R_c} - 225 \text{ for Aluminum winding}$$

$$\theta_h = \frac{R_h \times (235 + \theta_c)}{R_c} - 235 \text{ for Copper winding}$$

where

$$\theta_h = \text{Hot winding temperature (}^\circ\text{C)}$$

R_h = Hot resistance (Ω)

R_c = Cold resistance (Ω)

θ_c = Ambient temperature ($^\circ\text{C}$)

Rise in winding temperature (T_r) is obtained by



T_r = Average Oil temperature + Hot winding - Average oil rise during calculated temperature temperature total loss at shutdown at shutdown.

Thus final temperature rise is affected by winding material and transformer design affecting oil cooling after shutdown [3].

A. Use of software

Curve fitting [4] [5] is carried out and value of shut down resistance is extrapolated from measured resistance values. Curve fitting involves finding a mathematical relationship that best represents the trend in the given data, while extrapolation uses that relationship to predict values beyond the observed range. It helps in analyzing patterns, forecasting future values and understanding trends, though predictions can become less reliable the further they extend from the original data. This is because the fitted curve may not fully represent the underlying physical behavior when extrapolation is made over a longer period outside the observed interval.

B. Present curve fitting approach

After shutdown, the temperature decreases over time in a nonlinear (exponential-like) manner. The behavior is due to complexity of transformer thermal circuit [6] [7] which varies with transformer design. Considering this nature, curves such as

Linear curve, Parabolic curve, Cubic curve other than traditional Exponential curve are considered.

Whereas standards like IS 2026-2 (2010) [8] & IEC 60076-2 (2011) [9] describes using a combination curve of type as follows:

$$R(t) = A(t) + B \times e^{-t/T}$$

Where $A(t)$ can be a constant or linear function, B is a winding to liquid gradient parameter, T is winding time constant.

IEEE Standard C57.12.90 [10] requires the use of a computerized least-squares exponential curve-fitting program only for extrapolation of post-shutdown hot resistance measurements to the instant of shutdown.

The comparison of each standard regarding interpretation of resistance curve fitting is shown in Table 1.

In this paper, only single function curves limited to single exponential, quadratic, linear & cubic are analyzed.

In this study rms error is taken as goodness of fit criteria.

C. Experimental Results

Here selection of accurate order/nature of curve is ascertained after making required curve fitting then evaluating RMS error of curve to find best fitting curve out of possible/relevant curves. Here quadratic, cubic, linear & exponential curves are compared.

During the experiments transformers were fed required values of losses and current, as per standard procedure and temperature values of top oil, radiator top, radiator bottom and average ambient temperatures were recorded. During shutdown, resistance of windings was measured after disconnecting the supply and setting up resistance measuring kit. The time consumed in setting up resistance measuring kit is the main reason that resistance cannot be measured at the shutdown instant. For this resistance variation is recorded at regular time after shutdown then extrapolated to get the resistance exactly at time of shutdown. During the experiments, resistance of LV winding is only considered.

Total of 10 number of 3-phase, 11000/433 V, ONAN, distribution transformers with Dyn-11 as vector group were taken into consideration, & the extrapolated graphs of LV winding resistances of those transformers are shown in Fig. 1 to Fig 5,

along with RMS errors for each curve type in every experiment. Table 2 shows concise variation in rms error for each experiment along with curve type.



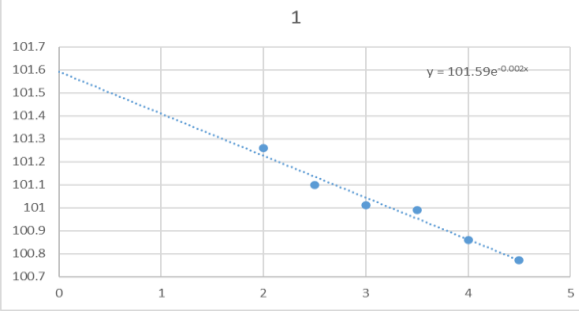
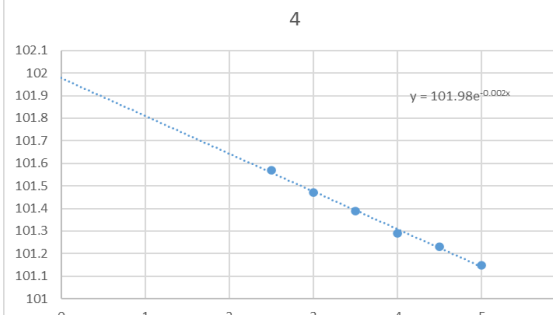
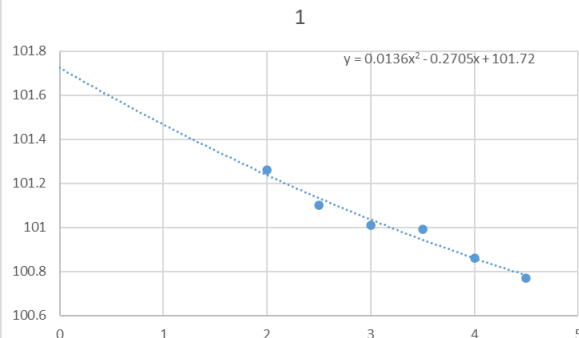
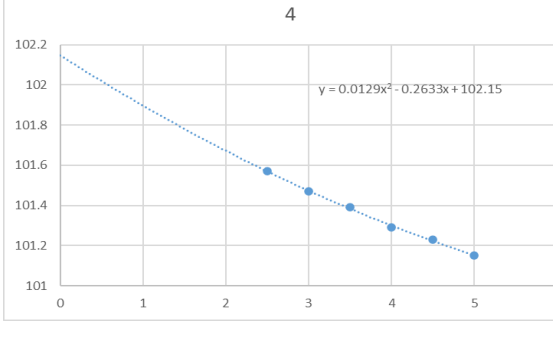
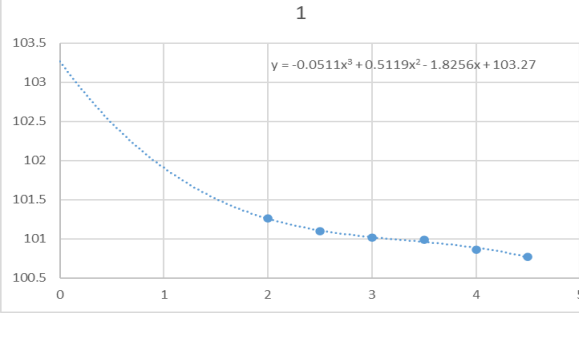
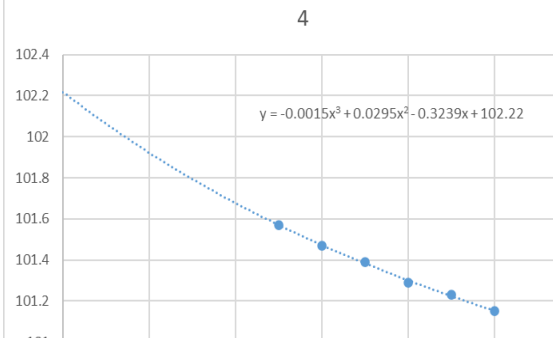
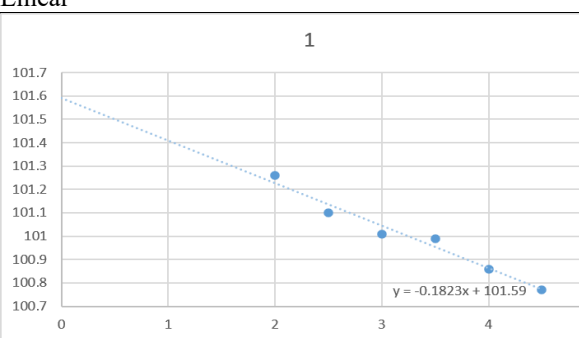
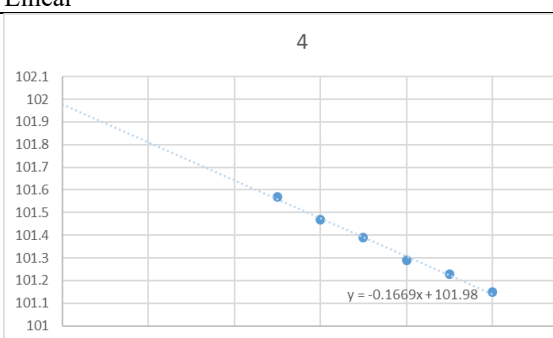
Experiment 1 (25kVA)		Experiment 4(25 kVA)	
Exponential	rms error	Exponential	rms error
	0.2576		0.3631
Quadratic	rms error	Quadratic	rms error
	0.1521		0.0762
Cubic	rms error	Cubic	rms error
	0.1176		0.0693
Linear	rms error	Linear	rms error
	0.1533		0.0916

Fig.1. Graphical curve fitting results for experiment 1 & 4



Experiment 3(100 kVA)		Experiment 2(63 kVA)	
Exponential	rms error	Exponential	rms error
3	0.1245	2	0.1797
Quadratic	rms error	Quadratic	rms error
3	0.0277	2	0.0228
Cubic	rms error	Cubic	rms error
3	0.0450	2	0.0436
Linear	rms error	Linear	rms error

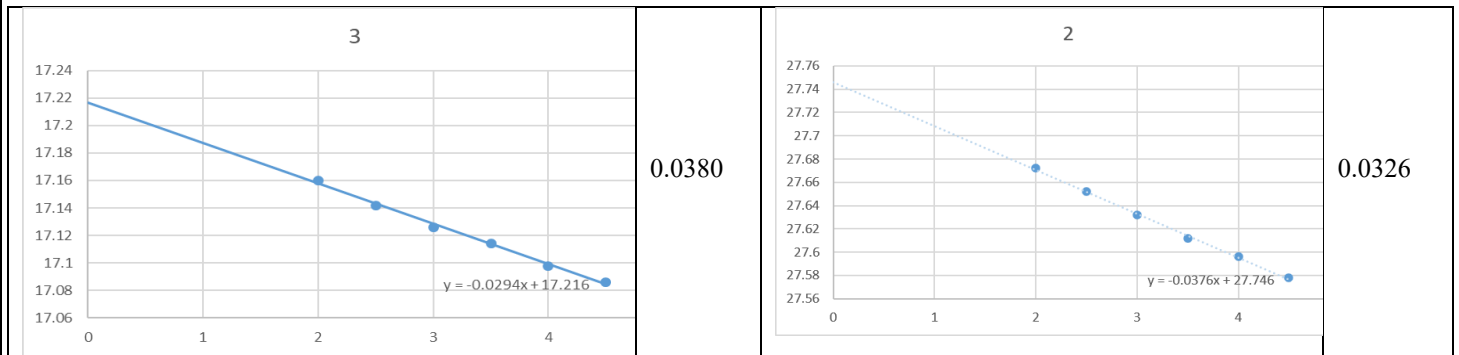


Fig.2. Graphical curve fitting results for experiment 3 & 2

Experiment 5(100 kVA)		Experiment 8(100 kVA)	
Exponential	rms error	Exponential	rms error
	0.0991		0.1538
Quadratic	rms error	Quadratic	rms error
	0.832×10^{-07}		0.0399
Cubic	rms error	Cubic	rms error

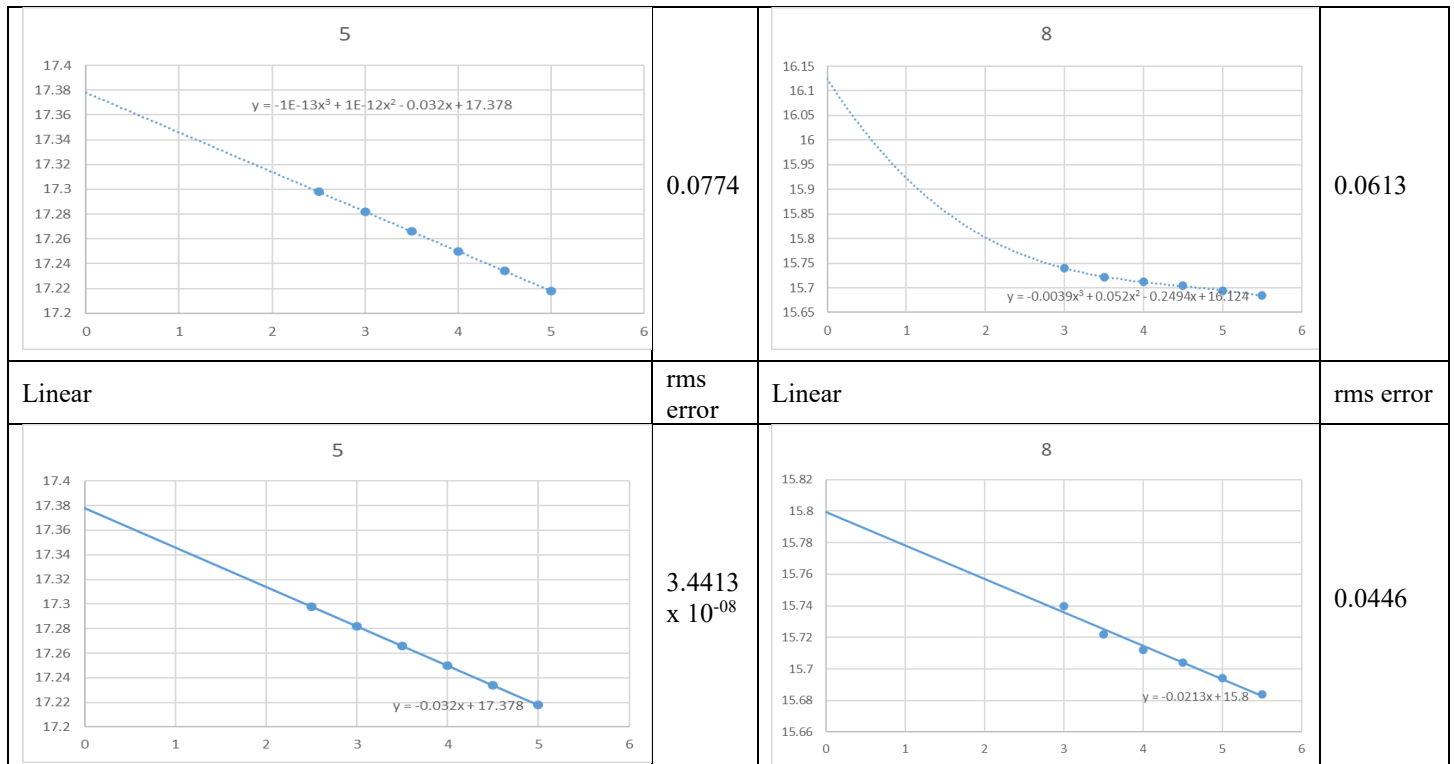


Fig.3. Graphical curve fitting results for experiment 5 & 8

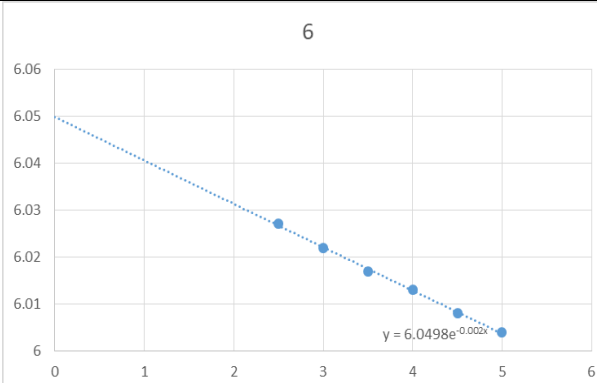
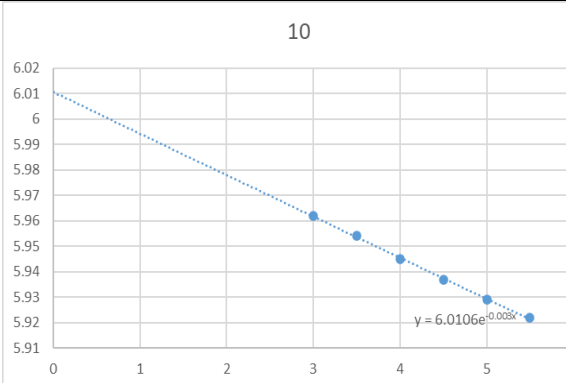
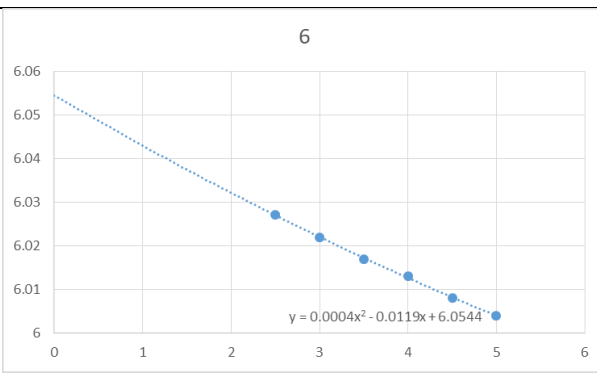
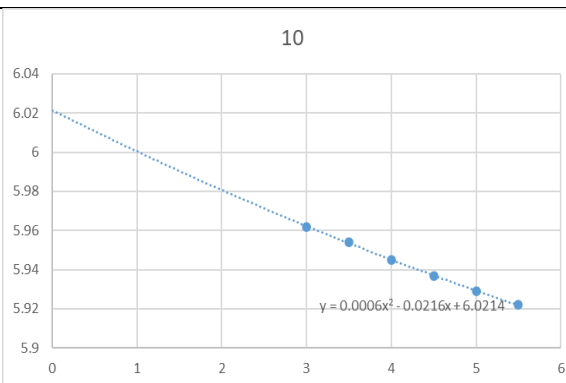
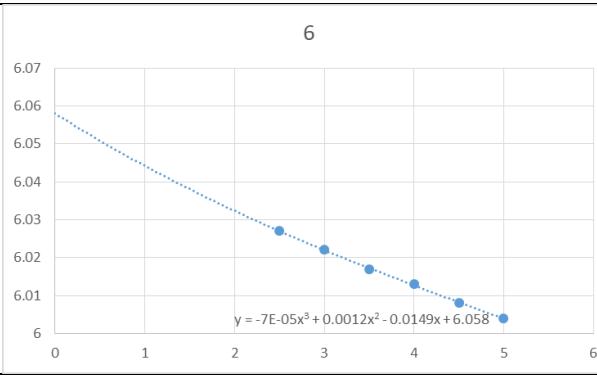
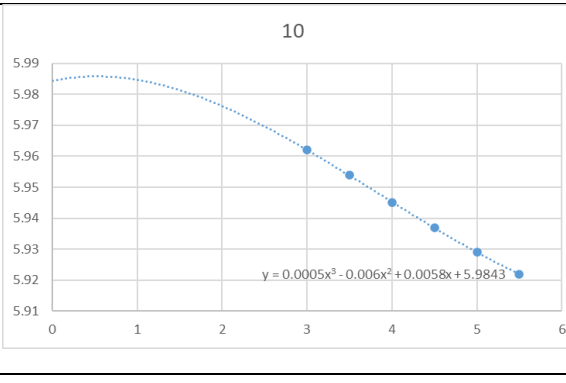
Experiment 7(250 kVA)		Experiment 9(250kVA)	
Exponential	rms error	Exponential	rms error
	0.0949		0.0573
Quadratic	rms error	Quadratic	rms error



7 $y = -4E-05x^3 - 0.0201x + 6.0744$	0.0268	9 $y = 0.0004x^3 - 0.0147x + 5.5291$	0.0312
Cubic	rms error	Cubic	rms error
7 $y = 0.0019x^3 - 0.0213x^2 + 0.0572x + 5.9837$	N/A	9 $y = 0.0004x^3 - 0.0044x^2 + 0.0049x + 5.5027$	N/A
Linear	rms error	Linear	rms error
7 $y = -0.0204x + 6.0748$	0.0264	9 $y = -0.0117x + 5.523$	0.0160

Fig.4. Graphical curve fitting results for experiment 7 & 9



Experiment 6(200 kVA)		Experiment 10(250 kVA)	
Exponential		Exponential	rms error
			0.0838
Quadratic		Quadratic	rms error
			0.0250
Cubic		Cubic	rms error
			N/A
Linear		Linear	rms error

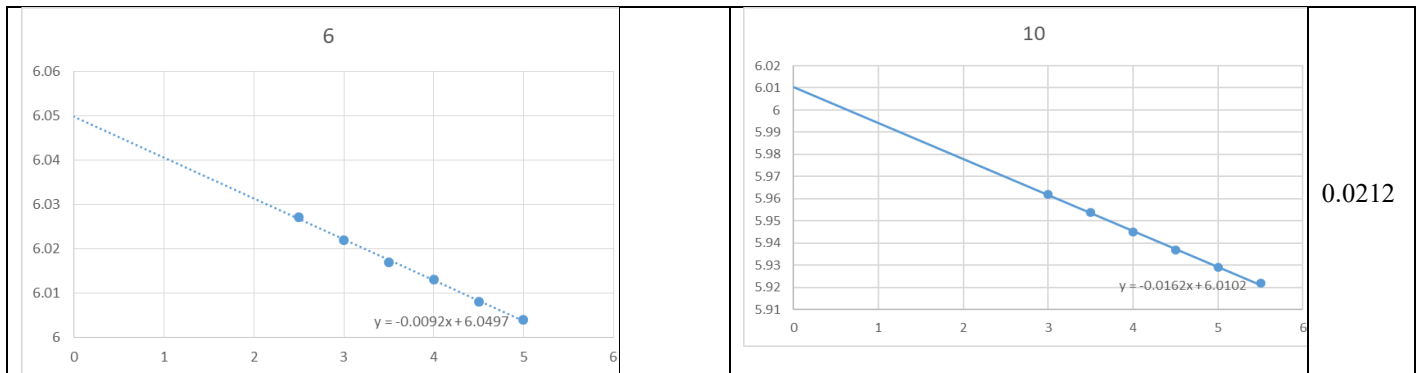


Fig.5. Graphical curve fitting results for experiment 6 & 10

Table.1. Comparison of standards IS 2026 (Part 2) / IEC 60076-2/ IEEE C57.12.90 regarding interpretation of resistance curve fitting.

COMPARISON ASPECT	IS 2026 (Part 2)	IEC 60076-2	IEEE C57.12.90
Primary methodology	Uses resistance method for winding temperature determination after shutdown. Requires extrapolation of measured resistance to the instant of shutdown.	Same as IS 2026 because IS 2026 is technically harmonized with IEC 60076-2.	Provides two methods: (1) empirical correction method and (2) cooling curve method depending on transformer characteristics
Resistance measurements after shutdown	Hot resistance measured immediately after de-energization and continued until sufficient cooling data are obtained.	Same requirement	Requires at least four resistance measurements for cooling curve method (older editions). Later editions require much denser sampling.
Time for first reading	As soon as practicable after shutdown.	Same.	First reading after inductive effects disappear and within 4 minutes after shutdown
Curve fitting requirement	States that resistance values are extrapolated back to shut down. Does not prescribe a mathematical fitting equation or algorithm	Same. No prescribed regression technique	Earlier editions: "draw a smooth curve" or use a curve fitting program. Later editions (2015 onward): explicitly recommends least-squares exponential decay fitting
Specified mathematical model	None	None	1999/2006 editions: no mathematical model specified. 2015 edition: exponential decay fitted using least squares.
Coordinate system specified	Not specified.	Not specified.	Older editions simply mention plotting on suitable coordinate paper. No requirement for linear, logarithmic, or semi-log axes.
Regression algorithm defined?	No	No	Only from IEEE C57.12.90-2015 onward: least-squares exponential regression explicitly identified. Earlier editions do not specify regression methodology



Number of resistance points	Not explicitly specified beyond obtaining sufficient data.	Same.	Minimum four readings (1999/2006). Later editions require closely spaced measurements (10–30 s intervals depending on transformer type).
Sampling interval	Not specified.	Not specified.	Newer editions specify intervals (10–15 s or 30 s depending on transformer class). Earlier editions do not.
Extrapolation target	Resistance at $t = 0$ (instant of shutdown).	Same.	Resistance at instant of shutdown, used to calculate average winding temperature.

Table.1. (Continued) Comparison of standards IS 2026 (Part 2) / IEC 60076-2/ IEEE C57.12.90 regarding interpretation of resistance curve fitting.

Acceptance criteria for fitted curve	Not specified.	Not specified.	No goodness-of-fit criteria (e.g., R^2 or residual limits) specified.
Treatment of multiple phases	Measure each winding as required.	Same.	Correction from one phase may be applied to other phases if their first readings are within 4 minutes.
Guidance on software	None	None	Newer editions explicitly allow computerized curve fitting. Earlier editions only mention smooth-curve extrapolation.
INFERENCE	Provides the test principle but leaves the entire curve-fitting methodology to the testing laboratory, allowing different implementations.	IEC philosophy is performance-based rather than algorithm based; laboratories are free to choose extrapolation techniques provided the result is technically justified.	IEEE is considerably more prescriptive. Earlier editions still left ambiguity, but from the 2015 revision onward the standard moves toward a standardized least-squares exponential fitting approach, improving repeatability between laboratories.

Table.2. rms error values for different curves for transformer resistance variation after temperature rise test (cells marked green represent lower rms error corresponding to Experiment Number & curve type)

TABLE: 2				
	Exponential	Quadratic	Cubic	Linear
Exp. 1	0.2576	0.1521	0.1176	0.1533
Exp. 2	0.1797	0.0228	0.0436	0.0326
Exp. 3	0.1245	0.0277	0.0450	0.0380
Exp. 4	0.3631	0.0762	0.0693	0.0916
Exp. 5	0.0991	3.832×10^{-07}	0.0774	3.4413×10^{-08}
Exp. 6	0.1027	0.0229	0.0210	0.0163
Exp. 7	0.0949	0.0268	--	0.0264
Exp. 8	0.1538	0.0399	0.0613	0.0446
Exp. 9	0.0573	0.0312	--	0.0160
Exp. 10	0.0838	0.0250	--	0.0212



IV. OBSERVATIONS

1. Each curve-fitting method produces a different RMS error. In a large number of test cases among the tested samples, quadratic and linear curves exhibit the lowest RMS errors among the four fitting methods.
2. The fitting curves must be evaluated individually for each temperature-rise test and compared based on RMS error and the overall shape of the fitted curve.
3. Although winding cooling is generally associated with Newton's law of cooling, a single exponential fit exhibits relatively higher errors in the considered cases. This may be attributed to the complex, non-ideal cooling behaviour of transformer windings in an oil-cooled environment.
4. The lower error in polynomial as compared to single exponential is due to the fact that transformer cooling is a complex phenomenon including different time constants. This phenomenon cannot be described by single exponential leading to larger RMS error. However a polynomial is empirical approximation of given data and relates to this multiple exponential function, as polynomial expansion of the same phenomenon.
5. Abnormal variations are observed in the cubic fits for Experiments 7, 9, and 10. These cases indicate that higher-order curves may closely fit measured resistance values while deviating significantly at distant time points.
6. Resistance variation is influenced by transformer cooling characteristics. Differences in transformer design alter the thermal circuit, thereby affecting the temperature variation profile. This is evident from different nature of curve even for transformer of same rating as compared side by side in Figures 1, 3 & 4.

V. CONCLUSION

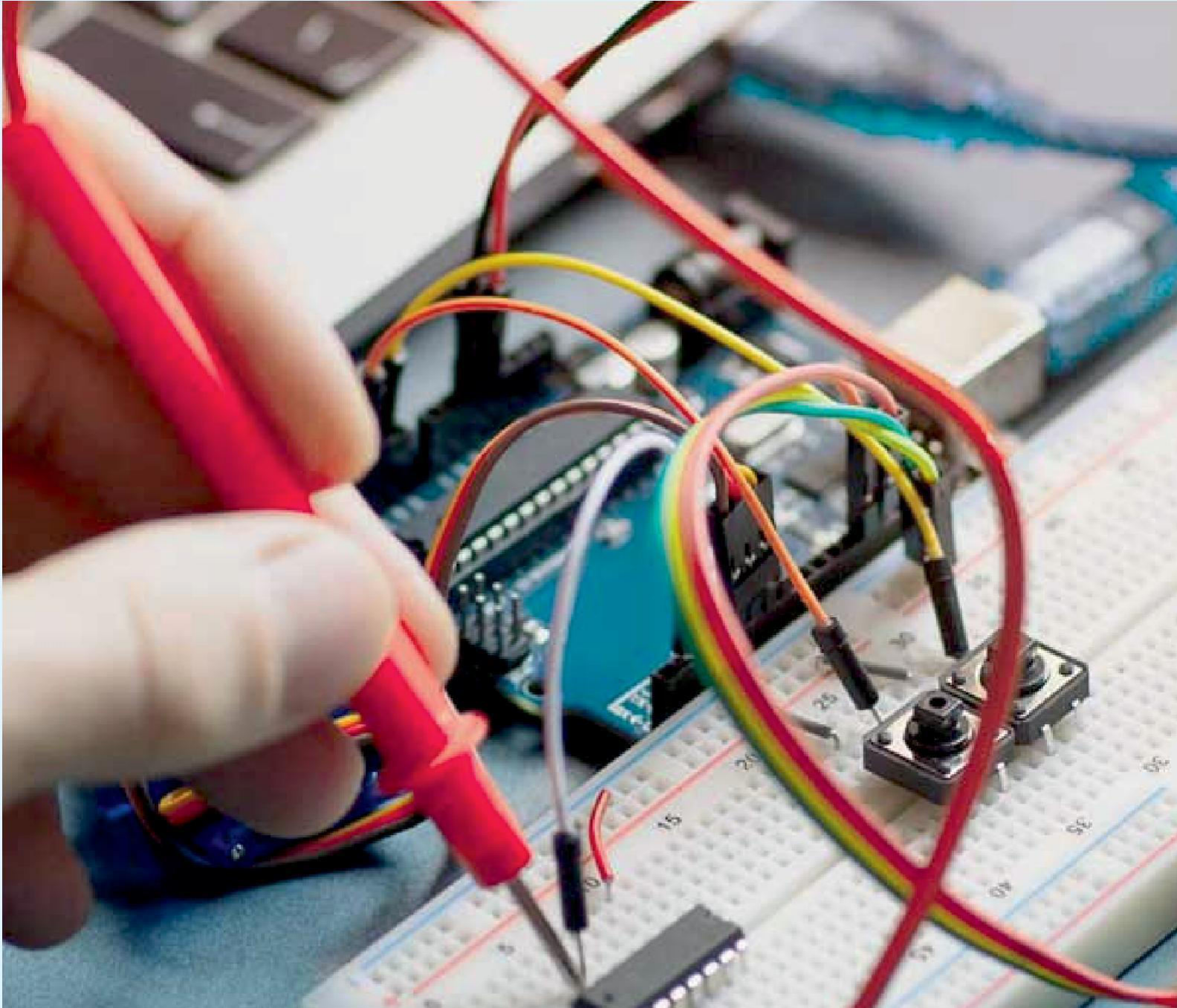
The most appropriate curve-fitting should be selected individually for each temperature-rise test by considering both RMS error and the physical variation of the fitted curve. Although higher-order curves may provide better fitting accuracy, abnormal deviations must be carefully examined to avoid unreliable extrapolation. The observed variations in cooling behaviour also highlight the influence of transformer design and thermal characteristics on the estimation of winding temperature.

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