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Role of Tan Delta Measurement Technique in Power Transformer Moisture Condition Assessment at Factory and Field Level

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ABSTRACT: It is well known fact that transformer play a crucial role in substations and switchyards, and the failure of this can have a significant impact on the reliability, availability, and cost of power supply. As society's reliance on electricity for development continues to grow, utilities face increasing pressure to meet the rising demands for a dependable power supply. Economic considerations play a substantial role, leading utilities to adopt a common policy of maximizing the utilization of existing networks to minimize capital expenditure on new equipment. Achieving this objective requires placing paramount importance on maintenance practices.

A comprehensive review of the literature reveals that transformer failures often stem from insufficient maintenance, improper operation, severe weather conditions, and manufacturing or design defects, rather than simply insulation ageing. To address these challenges, utilities must implement a systematic Operations and Maintenance approach that incorporates diagnostic tests to assess the condition and conduct health check-ups on equipment.

KEYWORDS: Tan delta measurement, Solid Insulation, Moisture content, Power transformer

I. INTRODUCTION

Moisture existing in the winding paper insulation is a crucial factor in assessing the condition of power transformers. Moisture can enter the insulation from the atmosphere during commissioning and maintenance, and an increase in moisture content accelerates the aging of the paper insulation. Additionally, moisture gets generate in transformer as a byproduct due to aging process itself. Moisture development in oil-paper insulation has dangerous effects, such as reducing dielectric strength, speeding up cellulose aging, and creating gas bubbles at high temperatures [1]. These factors significantly increase the risk of sudden electrical failure. Therefore, exact determination of the moisture content within the insulation is essential for assessing the reliability and lifespan of a transformer. Unlike conventional methods, which are often imprecise, our testing systems use dielectric measurements to determine moisture levels.

A significant proportion of failures in power Transformers result from the deterioration of insulation. Moisture content conditions of power transformers can be known by accurate interpretation of capacitance and tan delta test results of power transformers which typically requires understanding the construction of the apparatus and the characteristics of the specific insulation types employed. Deviations from the normal tan delta results of insulation materials can signal abnormal conditions such as the presence of moisture content in solid or liquid insulation systems of transformers. Tan delta measurements provide insights into various conditions affecting the insulation of a diverse range of power transformers [2]. These conditions include chemical degradation over time and due to temperature, encompassing instances of acute deterioration triggered by localized overheating, contamination caused by water, carbon deposits, substandard oil, dirt, and other chemical substances, significant leakage through cracks and over surfaces of transformer condenser bushings and Ionization . The interpretation of tan delta measurements typically relies on accumulated experience, the transformer manufacturer's recommendations, and the observation of differences like discrepancies in measurements on the same unit after successive time intervals, variances in measurements between duplicate units or similar components of one unit, tested under identical conditions around the same time and differences in measurements at various test voltages on one part of a unit [3]. An increase in the slope (tip-up) of tan delta versus voltage curve at a specific voltage indicates the initiation of ionization at that voltage.

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II. SOURCES OF MOISTURE IN POWER TRANSFORMERS

Moisture contamination in transformer insulation can originate due to below three main sources:

1. Residual water content in the major insulation structural components that wasn't fully removed during factory drying out process.
2. Moisture absorbed during core coil assembly of transformers.
3. Moisture ingress from the atmosphere, which can occur through breathing during load cycles, leaking gaskets, faulty water traps, or exposure to humid air during site erection and maintenance or repair processes. This is the primary source of moisture buildup in transformers [4].

Early detection and repair of maintenance issues that allow moisture ingress are crucial, as drying and processing transformers is both costly and time-consuming. For instance, drying a 100 MVA transformer with 3-4 tons of insulation from 3% to 1.5% average humidity using the vapor phase method (usually done in the factory) takes just over 2 days. In contrast, using hot oil circulation combined with vacuum cycles would take nearly 10 days. Therefore, it is clearly preferable to prevent moisture ingress altogether.

III. IMPACT OF MOISTURE CONTENT ON TRANSFORMERS LIFE

Transformers operate with high efficiency due to the absence of rotating parts. However, certain parameters, such as losses and moisture content [5] in circulating oil and insulation paper, require regular monitoring, as they can impact the device's performance. Moisture is also produced as a by-product of the aging phenomena. Elevated moisture levels can shorten the transformer's lifespan, reduce dielectric strength, and compromise its loading capacity. Therefore, it is crucial to monitor and assess moisture content in transformers [6]. This paper provides a review of transformer insulation, the moisture mechanism, the effects of moisture, and moisture management strategies in transformers.
Moisture is one of the main threats to a transformer's lifespan, causing the materials to deteriorate rapidly over time. When there's an oil leak in the transformer or any part of the main tank is exposed to the environment, the transformer oil absorbs moisture from the air, which then accumulates within the oil [7]. Some of this moisture settles at the base of the transformer, leading to visible external corrosion. Additionally, moisture is absorbed into the insulation papers between the winding turns. Over time, this causes the insulation paper to deteriorate and break down, which can lead to short circuits between the windings and result in arcing faults inside the transformer.

IV. TECHNIQUES FOR MOISTURE CONDITION ASSESSMENT OF TRANSFORMERS

1. Karl Fischer Reagent Titration method:

Karl Fischer reagent titration method is an analytical chemistry method used to determine water content in PPM in a transformer oil sample through either volumetric or coulometric titration. Titration is a process to add a reagent of known concentration level to an unknown sample until their concentrations are balanced. This technique is widely used to assess moisture content in both liquid and solid insulation, and it serves as a base value for other methods, such as dielectric response methods [8]. However, the accuracy of Karl Fischer titration can be influenced by several factors, including moisture ingress due to humid atmosphere during sample preparation, sampling from transformers and transportation.

2. 50 Hz Tan delta measurement:

A tan delta/power factor measurement at line frequency (50/60 Hz) quantifies the combined losses in both oil and cellulose insulation. However, this measurement cannot differentiate between a dry transformer with aged service oil and a wet transformer with new oil [9]. Tan delta (dissipation factor) measurements are used to assess the healthiness of power transformers mixed insulation, which is critical for the transformers operation without any sort of breakdown. High oil conductivity, insulation aging, and increased moisture content are indicators of insulation degradation. These factors are also cause for higher losses, which can be measured through the power factor or dissipation factor.

3. Other Dielectric Response Methods:

Dielectric condition monitoring techniques determine water content level in solid paper-pressboard insulation based on dielectric properties such as recovery voltage method, polarization-depolarization currents measurement method, and frequency domain spectroscopy technique. The main reasons for developing dielectric response measurement techniques were the non-availability of any effective on-site moisture conditions assessment techniques and the unsatisfactory results from traditional equilibrium approaches [10]. Utilizing frequencies other than the standard line

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frequency enhances measurement sensitivity, as certain issues become more prominent at higher or lower frequencies. Modern test devices are capable of automatically performing frequency or voltage sweeps.

V. MEASUREMENT OF TAN DELTA OF POWER TRANSFOMER

Tan delta (dissipation factor) measurements are carried out to assess the condition of insulation any electrical power equipment. These insulation systems are critical to the electrical equipment's reliable operation. Indicators of insulation degradation include high transformer oil conductivity, aging of insulation, and increased water content level [9]. These factors lead to higher dielectric losses, which can be assessed by measuring the power factor or dissipation factor.

In power transformers, tan delta measurements are carried out on the main insulation sections i.e. between the windings and the insulation from the windings to the tank or earth. The windings are shorted together, transformer tank is earthed and a test voltage, mostly 10 KV is applied to one of the winding while the current through the insulation is measured on the other winding or the tank [6]. For transformers bushings, again the voltage is applied to the main bushing conductor, and the current is measured at the tap insulation point C2. The tan delta(δ) is calculated by taking the tangent of the angle δ between the measured current and the ideal current which would occur for loss free insulation system.

CPRI performed capacitance and tan delta measurement of various utilities northern India for many years of EHV sub-stations power transformers.

Doble/Megger make Automatic Insulation Analyzer were used for tan delta measurements. Tan delta (dissipation factor) represents the overall defects and dielectric losses in the insulation system of power transformers. In order to assess the state and quality of the entire mass of the transformer insulation, mainly following test modes are being used during the measurement of tan delta of transformer windings along with transformer condenser bushings [4]:

C_H : HV winding to tank (HV-E)
C_{HL} : HV winding to LV winding (HV-LV)
C_L : LV winding to tank (LV-E)
C_{LT} : LV winding to Tertiary winding (LV-TV)
C_T : Tertiary winding to tank (TV-E)
C_{HT} : HV winding to Tertiary winding (HV-TV)

The brief test procedure used for different circuit configuration as shown in Fig. 1, is tabulated in Table 1(a) and Table 1(b). The high voltage cable of instrument used for measurement is placed on the winding in the Energize column, and the low voltage lead is placed on the opposite winding.

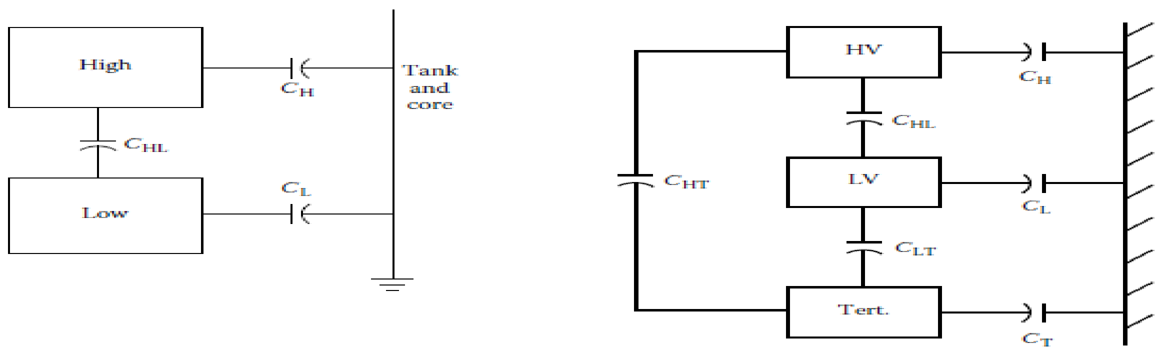

Fig.1: Insulation diagram of 2 wdg. & 3-Wdg. transformer

Table1 (a). Different test modes for 2-wdg. transformer

Test No.	Test Mode	Energize	Ground	Guard	UST	Measure
1.	GAR	High	-	Low	-	C_H
2.	UST	High	-	-	Low	C_{HL}
3.	GAR	Low	-	High	-	C_L

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Table1 (b). Different test modes for 3-wdg. Transformer

Test No.	Test Mode	Energize	Ground	Guard	UST	Measure
1.	GAR	High	-	Low, Tert.	-	C_H
2.	UST	High	Tert.	-	Low	C_{HL}
3.	GAR	Low	-	High, Tert.	-	C_L
4.	UST	Low	High	-	Tert.	C_{LT}
5.	GAR	Tert.	-	High, Low	-	C_T
6.	UST	Tert.	Low	-	High	C_{HT}

Interpretation of Test Results:

Modern oil-filled power transformers dielectric dissipation factor or tan delta values are less than 0.5% at 20°C test temperature [3]. In contrast, older power transformers, oil-filled distribution transformers, and various liquid-filled or dry-type power and distribution transformers might have power factors exceeding 0.5% but not more than 1% [6].

An elevated dissipation factor beyond typical values may signal conditions mentioned earlier, whether general or localized. A rise in dissipation factor often points to excessive moisture in the insulation [5].

For accurate measurements, it's crucial that bushing and pothead surfaces, terminal boards, etc., are clean and dry [3]. Any leakage over terminal surfaces might contribute to insulation losses, potentially yielding a false assessment of its condition if excessive.

VI. CASE STUDIES

Here few case studies have been discussed along with test data which includes measurement taken both at site and factory. It mostly reflects the causes of high tan delta values received.

CASE1:

First case study involves Tan delta measurement of 100 MVA, 220/66-33/11 KV, 3-winding Transformer-1 at 220 KV Substation in a utility, which was installed just two years back. When measurement was carried out 1st time, tan delta values for C_L (LV-E) and 66 kV B-Phase bushing were observed very high, although other insulation section tan delta values were also beyond permissible limit 0.5%. It was assumed that (LV-E) tan delta value is high because of faulty 66 kV B-Phase bushing which tan delta value was 9.66%. Therefore, next day again Transformer shutdown was taken and faulty bushing was replaced with a healthy bushing having tan delta value less than 0.31%. Again 2nd measurement of tan delta was repeated, but was no significant improvement in tan delta results of C_L (LV-E) insulation section of winding. It was observed 3.46, which is high.

This raised suspicions of a potential issue with the LV winding insulation section w.r.t. earth. It was clear that LV winding insulation with respect to Earth is contaminated with high moisture content level, which was reflected via high tan delta value. Maximum limit of water content is 1.25% by weight of water in insulation for transformers for 220kV or greater voltage class as per recommendations of international standards [5]. Also various research papers have shown that 1% tan delta values are approximately equivalent to 4% water content level in transformers insulation systems, which is higher to the recommended limits of moisture content level. The measurement values are provided in Table below:

Table 2: Tan delta test results of 100 MVA, 220/66-33/11 KV, 3-winding Transformer-1

Insulation Section / % Tan delta	C_H	C_L	C_T	C_{HL}	C_{HT}	C_{LT}
1st Measurement	0.70	3.80	0.93	0.86	0.87	0.66
2nd Measurement	0.68	3.46	0.89	0.84	0.86	0.65

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CASE 2:

Second case study again involves Tan delta measurement of 100 MVA, 220/66-33/11 KV, 3-winding Transformer-2 at another 220 KV Sub-station. This transformer was also installed almost two years back. When measurement was carried out, tan delta values for all insulation sections of winding were observed on higher side, while all bushings tan delta values were well within limit i.e. below 0.5%

This again raised suspicions of a potential issue with the winding insulation sections w.r.t. earth and each other. It was clear that windings solid insulation with respect to Earth and each other contained high moisture content level which is reflected via high tan delta values. The measurement values are provided in Table below:

Table 3: Tan delta test results of 100 MVA, 220/66-33/11 KV, 3-winding Transformer-2

Insulation- Section	C_H	C_L	C_T	C_{HL}	C_{HT}	C_{LT}
% Tan delta	0.73	1.76	1.00	0.79	0.83	0.58

CASE 3:

Third case study involves once again Tan delta measurement of another 100 MVA, 220/66-33/11 KV, 3-winding Transformer-3 at 220 KV Substation in utility. This transformer was also installed just within a year. When measurement was carried out first time, tan delta value for insulation section (LV-E) of winding was observed again on higher side, while bushings tan delta values and other winding insulation sections tan delta values were well within limit i.e. below 0.5% as shown in table below. Therefore, decision was taken to filter the transformer at site to improve the tan delta values. After drying out of transformer through filtration, again it was offered to measure tan delta after one month. But no significant improvement was observed in tan delta values.

This again raised suspicions of a potential issue with the LV winding insulation section w.r.t. earth. It was clear that LV winding solid insulation with respect to earth was containing high moisture content level and even it was not improved by using technique at site. The measurement values are provided in Table below:

Table 4: Tan delta test results of 100 MVA, 220/66-33/11 KV, 3-winding Transformer-3

Insulation Section / % Tan delta	C_H	C_L	C_T	C_{HL}	C_{HT}	C_{LT}
1st Measurement	0.49	1.41	0.72	0.47	0.51	0.40
2nd Measurement	0.42	1.29	0.63	0.42	0.46	0.37

CASE 4:

Fourth case study involves Tan delta measurement of 160 MVA, 220/132/11 KV auto power transformer at factory level during third party inspection. This transformer was offered for inspection before dispatch at site. When measurement was carried out, tan delta value for (HV+LV)-E insulation section was observed high, while bushings tan delta values and other insulation section tan delta values were well below within limits i.e less than 0.5%.

This raised suspicions of a potential issue again with (HV+LV)-E winding configuration. It was clear that this insulation section of winding contained high moisture content level which is reflected via high tan delta value. With this, it was concluded that at factory level transformer was not properly dried out using Vapour phase drying process. After all, decision was taken to send this transformer in VPD chamber once again for proper drying out. Few days after completing the drying process, again tan delta measurement was carried out and (HV+LV)-E insulation section tan delta value was drastically improved and was found well below 0.5%. The test data are mentioned in below Table:

Table 5: Tan delta test results of 160 MVA, 220/132/11 KV auto power transformer

Insulation- Section / % Tan delta	(HV+LV)-E	TV-E	(HV+LV) -TV
1st Measurement	1.10	0.28	0.37
2nd Measurement	0.32	0.24	0.32

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VII CORE STUDIES AND FINDINGS FROM TAN DELTA RESULTS OF TRANSFORMERS

From the above four case studies, it can be concluded that if tan delta values are more than 1% for transformers in service, moisture content level in transformer winding insulation sections may exceed beyond the permissible limits of % water content by weight in insulation[3]. Since arrangement of VPD (Vapor Phase drying machine) facility for drying out of transformers at site is very tedious and costly affair, therefore drying out of transformers by other alternative methods like filtration of transformer oil using filtration machine is not very effective technique for drying out transformer winding solid paper insulation section if transformer winding insulation sections are already contained higher moisture content level since its dispatch from factory. There is a possibility that the transformers mentioned in 1st, 2nd and 3rd case studies had been dispatched from factory itself with higher moisture content level present in winding insulation section without proper drying out the transformer at factory level, which is clear from case study-4 tan delta results of 160 MVA transformer.

VIII. CONCLUSIONS

Based on the findings from above Case studies, it becomes apparent that Tan delta measurements are highly effective tools for assessing the moisture conditions of power transformers. Care should be taken during tan delta measurements of transformers at factory level. Tan delta should be within acceptable range as per recommendations of international standards before acceptance of transformers at factory level. It should be ensured that transformers have been properly dried out by tan delta measurement test results. During measurement at site, the presence of conducted and radiated noise in measurement environments poses a challenge to obtain stable readings as the voltage level in the electric grid increases. However, tan delta measurements in paper-oil insulation systems of power transformers remain unaffected by applied voltage within 10 kV range. Therefore, tan delta measurements at 10 kV are proved suitable indicator to access the moisture conditions of Power transformers.

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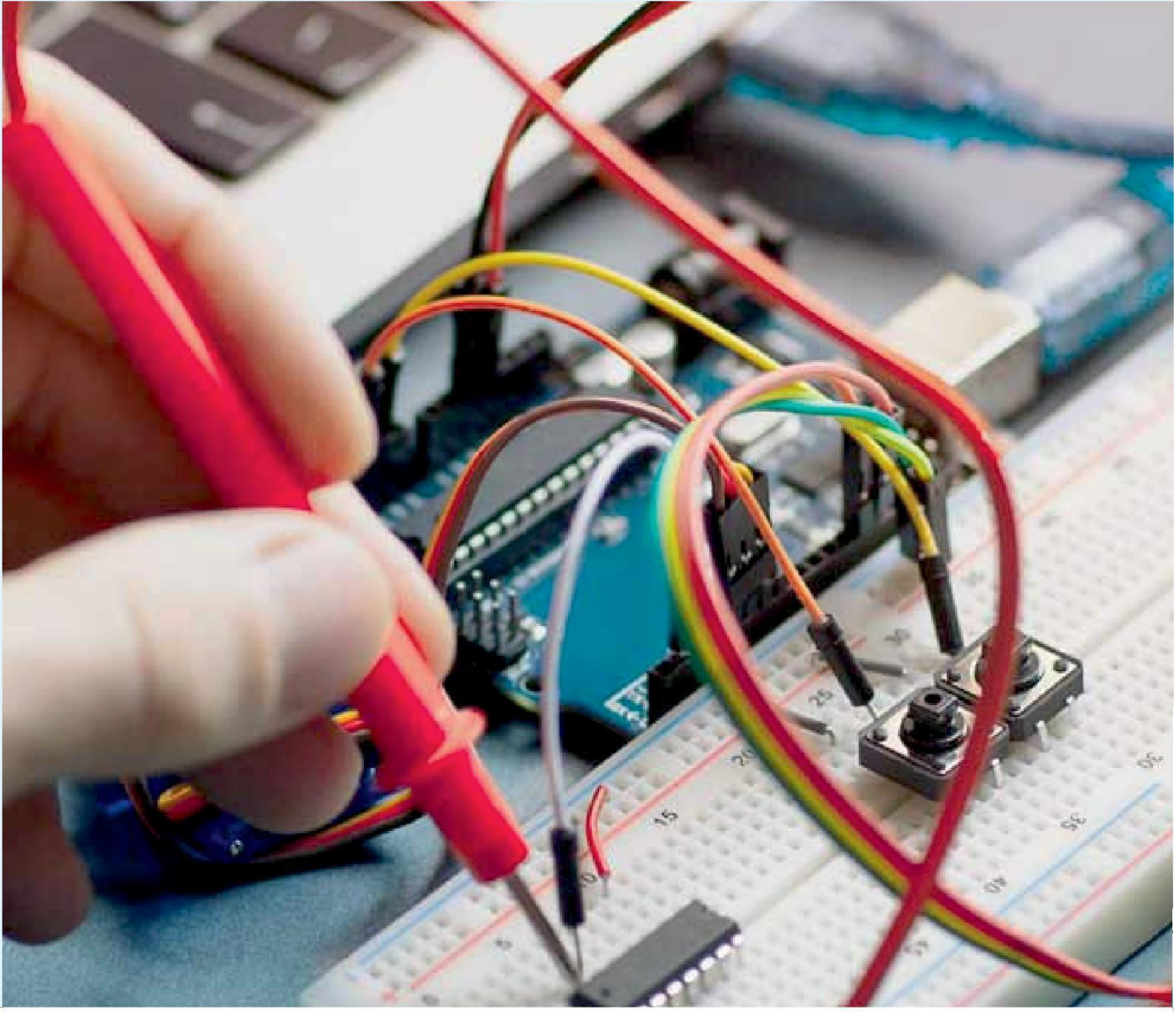

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