Design and Simulation of Temperature Rise in a Distribution Transformer

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Abstract - A Distribution Transformer is a vital component of a power system setup, providing the final consumer-friendly voltage to a household/industry, based on the demand of the consumer. The fabrication of these distribution transformers must be performed with intricate care and meticulous attention to the selection and assembly of each and every component involved. As these transformers are expected to survive for a duration of at least 20-25 years, monitoring the vital parameters of the transformer is crucial in understanding the health and functional capabilities of the transformer. Hence, it is of the utmost importance that these parameters are monitored on a constant basis and that these values are transmitted to an off-site moderator as efficiently as possible. This paper focuses on the design of a practically rated distribution transformer from scratch, which involves the individual design of each and every component involved within the transformer. Meticulous attention is also paid to the actual fabrication of the transformer itself, sufficing the required parameters specified during the design process and being capable of handling a practical load. A simulation of the temperature rise within the transformer is performed to demonstrate the adverse effects and significant impact of higher values of temperature on a practical distribution transformer.

Key Words: connection, system overloading, PROTEUS

1. INTRODUCTION

Distribution Transformers are a key part of a Power System setup as they help to step down the high voltages transmitted by the transmission lines to lower voltage values (of about 440V) and provide it for domestic/consumer use. Distribution Transformers can be mounted in multiple ways depending on the site it is being installed at and the use-case for the transformer itself (some examples are – pole-mounted, underground vaulted, etc.,). With an increase in demand/load, the number of distribution transformers being installed has increased exponentially. Hence, it is important to ensure the health/working condition of the transformer itself, as it is of vital importance to keep functioning for the power system to be operational. [1]

There are multiple parameters that influence the working of a distribution transformer (or any transformer) in its lifespan. However, the three main factors that majorly influence efficient functioning of a transformer are - Voltage, Current and Temperature. Other parameters like oil level, oil quality, overloading, etc., although aren't the major parameters influencing the functioning of a transformer, do have a significant impact on the functioning of the transformer. The biggest issue/plight that a distribution transformer can face right now is overheating. Hence, it is important that we constantly monitor these parameters to ensure proper functioning of the transformer.

The major goal to be accomplished with this process is to design a satisfactorily rated distribution transformer from scratch, which involves a multitude of steps and procedures which need to be executed as efficiently as possible. Another goal is to simulate the effect of overloading a practically rated transformer, so as to observe the adverse heating effects that can originate in each individual component of the transformer, which acts as a good lead to practically control the heating adversities observed in a real-time transformer.

2. SPECIFICATION AND DESIGN OF THE TRANSFORMER

The railway is a large power consumer that can cause uneven loading of the phases in the high voltage grid. This uneven loading by the utility may lead to voltage and current imbalance in the system and thereby affect other consumers connectedto the same network.

A three-phase power system is said to be balanced or symmetrical, if the voltages and currents have the same amplitude and each phase has a phase difference of 120°. Otherwise, it is termed an asymmetrical or unbalanced power system. A perfectly symmetrical power system does not occur due to some internal effects such as mutual coupling.

Voltage unbalance occurs mainly due to unbalanced currents at the points of common coupling drawn by unevenly distributed loads. Due to a significant amount of negative sequence current being injected into the system, the power systemcomponents will suffer from consequent negative effects such as overheating, additional losses of lines and transformers, interference with communication systems etc.

In order to reduce the effects of unbalance, several techniques can be applied depending upon the technological justification. A basic solution would be to distribute the loads evenly between the different phases. However, this method alone will not be sufficient due to the different traffic intensity occurring at each substation. The possible solutions can be categorized into two different types. First one is based on transformer connections, i.e., passive solutions. There are various types of specially connected transformers being employed in the railway substation, such as Scott transformer, V-V transformer, Leblanc transformers etc., and each connection has its own influence on treating the imbalance. These transformers are widely used in electrified railway systems as a load balancer.

Electrification of a railway line implies that the line can be operated by electric trains apart from diesel. Electrification involves large investments compared to diesel but operating costs are lower, as propulsion and maintenance are cheaper. The second one is based on controllable high voltage power electronic equipment, i.e., active solutions such as Conventional Static Var Compensators (SVC) or Voltage Source Converters (this part is not within the scope of this paper.

Table -1: Specifications of the designed transformer

Sl. No.	Transformer Parameter	Description/Value
1	Input Voltage	415V
2	Output Voltage	230V
3	Number of Phases	Single-Phase
4	Vector Group	Ii0
5	Type of Construction	Core-Type construction with 2 limbs/ Each limb carries 50% of primary and secondary windings
6	Capacity	2KVA
7	Conductor Used for Windings	Aluminium with super-enamel coating
8	Core Material	Cold-Rolled Non-Grain Oriented Silicon Steel
9	Total Weight	25 kg

These parameters are chosen in order to design a transformer capable enough to replicate the characteristics of a practically utilized transformer [2] while being small enough to perform various tests on it to determine the adverse heating and overloading effects that occur during a transformer's lifespan.

Once the specifications are finalized, the design process is commenced. The designing of the Transformer involves the calculation of multiple parameters of the transformer. It is of utmost importance that it is carried out as accurately as possible so that it doesn't affect the manufacturing process and the transformer fabricated can meet the desired specifications.

- **Volts/Turn**

To determine the volts per turn required for each winding, we use the formula which is given by –

Volts/turn = k$\sqrt{KVA}$ (where, k = 0.3 - 0.7 for oil cooled transformer)

Choosing k = 0.6, we get

Volts/turn = $0.6\sqrt{2}$

= 0.8485 ≈ **0.849 Volts/turn**

- **Primary Turns:**

The primary turns are given as the ratio of primary voltage to volts per turn i.e., $\frac{Voltage\ (Primary)}{Volts\ per\ turn}$ which here are $\frac{415}{0.849}\approx$ **489 Turns**

- **Volts/Turn (Actual)** Actual volts per turn is given by the formula: $\frac{Voltage}{Turns}=\frac{415}{489}=$ **0.84867 V**

- **Secondary Turns:**

Similarly, the secondary turns are given as the ratio of secondary voltage to volts per turn $\frac{Voltage\ (Secondary)}{Volts\ per\ turn}$, which here will be $\frac{230}{0.84867}\approx$ **272 Turns**

- **Core Area:** We know that the emf generated in the core is given by the formula e = 4.44×B×A×N×f×10⁻⁶(Where A is in mm^2 and B is in T)

$$\frac{e}{N}= 4.44\times B\times A\times f\times 10^{-6}$$

$$0.84867 = 4.44\times 1\times A\times 50\times 10^{-6}$$

$$A = \frac{0.84867}{4.44\times 1\times 50} \text{ x } 10^{-6} = 3828.84mm^2 \approx \mathbf{3828mm^2}$$

- **Gross Area:** Here the gross area which will be available is given by

$$\frac{Net\ Area}{0.9}=\frac{3828}{0.9}= \mathbf{4253.3mm^2}$$

- **Stacks used:** 40×100

2.1 Primary Design -

The design process of the primary windings of the transformer involves the calculation of the primary current, the inner and outer dimensions, along with the total weight of conductors and insulators used for the primary winding. Here, we use aluminum with a super-enamel coating as the conductor and insulator material respectively.

To design the primary side or the LV side of the transformer we have the following data:

Rating = 2KVA = **2000VA**

Voltage = **415V**

Current = $\frac{2000}{415}=$ **4.82A**

Turns/phase = **488**

Conductor size:

Choose a current density of 1.5A/mm^2 for oil cooled

Diameter is calculated by the formula given below

$$A = \frac{\pi d^2}{4}$$

$$d^2 = \frac{3.22\times 4}{\pi}$$

d = 2mm (bare) = **2.1mm (insulated)**

The insulation used for this conductor is super enamel - polyimide amide, dual coating. The inner coating expands and contracts with the conductor itself, while the outer coating provides the necessary insulation to the conductor.

No. of limbs here are 2, Turns per limb are $\frac{488}{2}$ = **244**
Number of layers = **5**
i.e., Turns per layer 49×4 and 48 turns in last layer
Winding length = (49 + 1) × 2.1 = **105mm**
End clearance will be 2 × 10mm
Window height = 105 + (2 × 10) = **125mm**
Inter layer insulation = 2mil of mylar = **0.0508mm**
Radical thickness of primary=(2.1×5) + (5× 0.0508) = **11mm**
Core inner dimension = 40×100
Core to primary clearance = 3.5 + 3 = **6.5mm**
Inner dimension of primary is (40 + (6.5×2)) + (100 + (6.5×2)) = **53×113 mm²**
Outer dimension of primary is (53 + (11×2)) + (113 + (11×2)) = **75×115 mm²**
Length of one turn (LMT) = $[\frac{53+}{2} + \frac{113+1}{2}] \times 2$ = 376mm = **0.376m**
Wire length = LMT × turns/limb × 2 + tolerance (1%) = 0.376 × 244 × 2 × 1.01 (tolerance) = **186m**
Resistance /phase at 75° (R_{75°) is given by the formula $\frac{\rho \times l}{A}$ (ρ= 0.0346 for Al at 75°)

$R_{75^\circ} = \frac{0.0346 \times LMT \times 244}{A}$ (here $A = \frac{\pi \times 2^2}{4} = 3.14mm^2$)

$R_{75^\circ} = \frac{0.0346 \times 0.376 \times 244}{3.14}$ = **1.01Ω**

$R_{28^\circ} = R_{75^\circ} \text{ x } \frac{225+28}{225+75}$

$= 1.01 \text{ x } \frac{225+28}{225+75}$

= 0.8517Ω ≈ **0.852Ω**

Bare weight of the conductor is given as the product of volume and density i.e., Volume ×Density
= L×A×Density
= LMT×224×2×3.14×2.703×10⁻³ Kg
= **1.56Kg**

Insulated weight = $\left[\frac{(2.1)^2-(2)^2}{(2)^2} \times \frac{1.8}{2.703} + 1\right]$ x 1.56
= 1.66Kg ≈1.7Kg ×1.1(Tolerance) ≈ **1.8Kg**

The density of the core used is= 7.65g/cc.
These are the various parameters required to be calculated for the primary/LV region of the distribution transformer.

2.2 Secondary Design -

The secondary/HV design follows the same procedure as the primary design, wherein the inner dimensions of the entire winding, the diameter of the windings used and the length of the wire used is determined.

To design the secondary side or the HV side of the transformer we have the following data:

Inner dimension of secondary (75+(6×2))×(135+(6×2)) = 87×147

Secondary current = $\frac{2000}{230}$ ≈ **8.7A**

Cross section = $\frac{8.7}{1.5}$ ≈ **5.8 mm²**

$5.8\boldsymbol{mm^2} = \frac{\pi d^2}{4}$

d = 2.717mm (Bare) ≈ 2.8mm (Insulated)

Cross section = $\frac{\pi \text{ x } 2.7^2}{4}$ = 5.725

Current density $\frac{8.7}{5.725}$ x 1.519 ≈ **1.52A/mm**

The winding length of the secondary winding should be equal to or less than the inner winding, so we get Secondary turns as 272.

And, Turns per limb as $\frac{272}{2}$ = **136 turns**

Therefore, Turns per layer = $\frac{Winding\ length}{insulated\ diameter}$ = 1

$= \frac{105}{2.8} + 1 \approx 36$

Number of turns = $\frac{136}{36}$ ≈ **4 turns**

To make the windings uniform, we take **34×4 turns**

Winding length = **100mm (35×2.8)**

End clearance = **12.5mm**

Radial thickness = (2.8×4) + (3×0.0508) = 11.352mm ≈ **12mm**

Outer dimension = (87 + (12 × 2)) × (147 +(12×2)) = **111×171 mm²**

Length of one turn (**LMT**) = $[\frac{87+111}{2} + \frac{147+171}{2}] \times 2$ = 516mm = **0.516m**

Wire length = LMT×turns/limb×2 + tolerance (1%) = 0.516×136×2×1.01 (tolerance) = **142m**

Resistance /phase at 75° (R_{75°) = $\frac{\rho \times l}{A}$ (ρ= 0.0346 for Al at 75°)

$= \frac{0.0346 \times LMT \times 244}{A}$

$= \frac{0.0346 \times 0.516 \times 136}{5.725}$ = **0.43Ω**

$R_{30^\circ} = R_{75^\circ} \times \frac{225+28}{225+75}$

$= 0.43 \times \frac{225+30}{225+75}$ = **0.3655Ω**

Bare weight as we know is the product of volume and density i.e., volume ×Density

= L×A×Density

= LMT×136×2×5.725×2.703×10⁻³ Kg

= **2.18Kg**

Insulated weight = $\left[\frac{(2.8)^2-(2.7)^2}{(2.7)^2} \times \frac{1.85}{2.703} + 1\right]$ ×2.18

= 2.29Kg ×1.01(Tolerance) ≈ **2.32Kg**

2.3 Core Design -

For the core of the transformer, Cold-Rolled Non-Grain Oriented (CRNO) silicon steel is utilized, as it helps minimizing core losses. In the design process of the core, the core weight along with the losses observed in the transformer are evaluated.

Cross-section of core will be 4 ×100 with 95% reduction

= 4 ×100×0.95 = **3800mm^2**

Weight of the core is given as the product of length, area, and density = 570 ×3800 ×765×10^{-6} = **16.6Kg**
Core loss = Core Weight×Specific Loss×Build Factor
= 16.6×3×1.3
= **65W**
Primary Load Loss as we know is denoted by P_{LL} and given by
P_{LL}= 3×I^2 R = 3×4.82^2×1.01 = **71W**
Secondary load loss: P_{LL}= 3×I^2 R = 3×8.7^2×0.43 = **98W**

Total loss is given by the sum of primary and secondary load loss, core loss, and stray or tank loss(2W/KVA), which will be - $P_{L(Total)}$ = 71 + 98 + 65 + 6 = **240W**

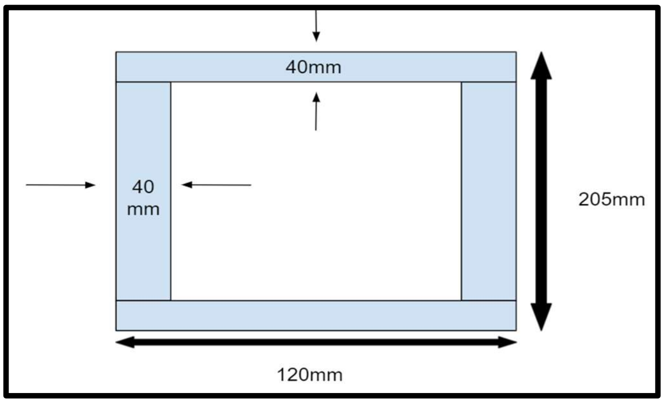

Fig 1- 2-Dimensional view of the designed core.

2.4 Tank Design -

The entire transformer must be placed in a tank capable enough to occupy the entire construction, along with some headroom for any additional accessories or oil that might be poured into it to cool the transformer unit.

To design the tank, certain parameters like depth, capacity, and oil in the tank are to be formulated which is done as shown below -

Depth of tank: 171 + (2×20) = 211mm ≈ **215mm**

Capacity of tank: l×b×h (dm³) = 2.75×2.75×2.15=**16.2 Litres**

Displacement: $\frac{16.6\ (mass)}{7.65\ (Density)}+\frac{1.56+2.18}{2.703}+\frac{2.7}{7.65}$= 3.89 ≈ **4 Litres**

Oil in tank = Capacity - Displacement =16.2-4=12.2≈**13 Litres**

Core clamp = 40×40 L-angle clamps for core
Length = 275×4 = 1100mm = **1.1m**
Weight with additional 1% tolerance factor=1.1×2.4=**2.64 Kg**

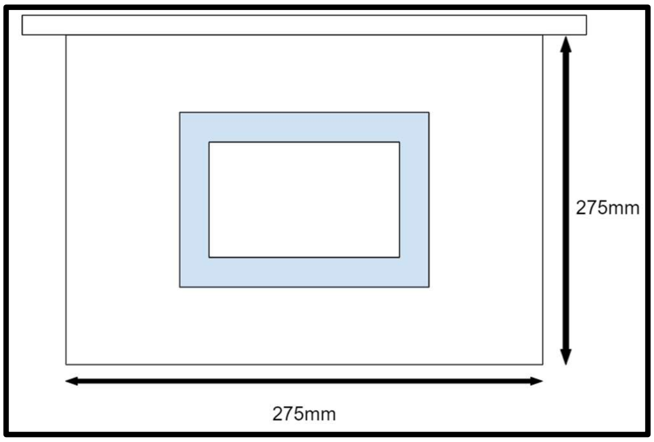

Fig 2- Illustration of the designed tank, along with the core.

Once all the calculations for all the parts of the transformer are concluded, the design sheet is provided to the manufacturer to fabricate the transformer. These parameters are vital to a manufacturer to efficiently manufacture the transformer to the required specifications of the designer.

The fabricated transformer has a fiberglass nameplate with multiple sensors connected internally to the primary, secondary windings and the core.

Fig. 3 - Front view of the fabricated transformer

3. SIMULATION OF TEMPERATURE RISE IN A TRANSFORMER

In a practical temperature rise test of the distribution transformer, the transformer would be connected to a sinusoidal 415V source, with a variable load of 8A, capable of reaching 10A connected to it. This setup would help us practically observe the hotspots that might be created within the core as well as in the windings of the transformer. This phenomenon can also be simulated to an extent to provide satisfactory details regarding the temperature rise in the distribution transformer.

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To simulate a highly rated distribution transformer environment, the Proteus Design Studio software was utilized [3], which provides the essential tools needed to simulate the temperature rise that can occur in the fabricated distribution transformer. The Proteus Suite is available in multiple configurations, depending on the design and simulation that one wishes to achieve. For our test case, we utilized the Schematic Capture and Microcontroller Simulation libraries to get the necessary components for the test.

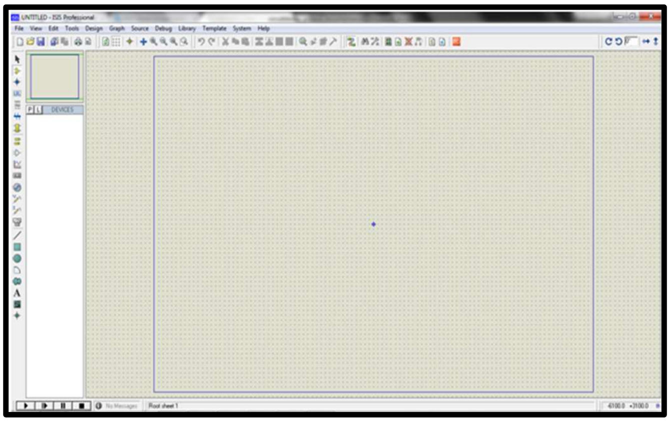

Fig. 4 - The Proteus Design Studio Environment

Initially in the Proteus environment, the design sheet is set up by specifying the libraries needed for the simulation. Once the design sheet is initialized, the required components can be picked up from the Component Mode menu on the left-hand side of the design sheet.

The components used for the simulation were as follows -

- The transformer used was a 415/230V, single-phase, ideal transformer with 1.75 turns ratio.
- A sinusoidal AC input source of 415V.
- A typical voltage sensor and current sensor were connected in parallel and series respectively.
- An LM35 Sensor was connected to the secondary winding of the transformer, which received its supply from an Arduino Uno board, powered by a 5V source.
- A 30-ohm resistor was used as the load, which drew a current between 8-10A on varying it. This is crucial to simulate the practical temperature rise occurring on the transformer.
- A virtual terminal was also connected to visualize the temperature values obtained from the LM35 current sensor. [4]. After the completion of the selection and configuration of the components needed for the simulation, all the components are connected as per the circuit diagram represented below. The LM35 sensor gets its input from the Arduino board itself, which has a neat provision of an in-built power source to boot it up during the simulation. The virtual terminal is also interfaced with the Arduino itself to get the necessary temperature readings.

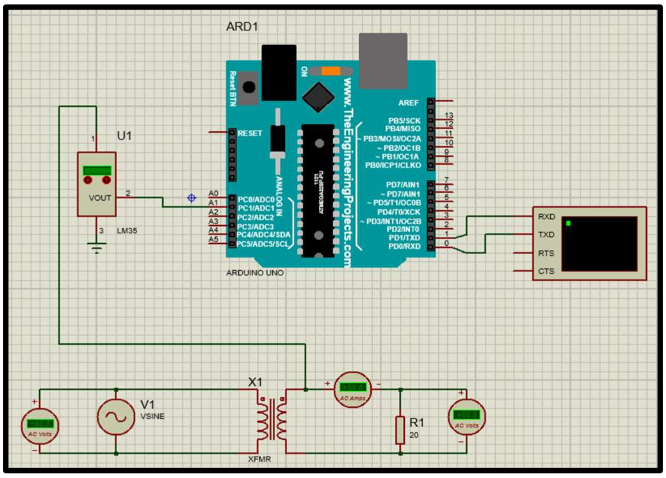

Fig. 5 - Circuit diagram of the simulation setup in Proteus

Once the circuit diagram is completed, the following steps are followed to simulate the transformer setup -

1. First, the ideal transformer is connected to the sinusoidal AC source on the primary side, while the voltage and current sensors are connected on the secondary side.
2. The LM35 temperature sensor is also connected on the secondary winding, which receives its 5V supply from the Arduino board.
3. A 30 ohms variable load, drawing a current between 8-10A is finally connected to the transformer. On completion of the circuit, the design is saved and is ready to be simulated.
4. As the temperature rise within the transformer is gradual and takes some time to be reflected on the sensor, the simulation is run for a duration of 15-20 minutes
5. Now, the simulation is made to run, and the temperature values from the sensor are obtained at an interval of 30 seconds per reading. This interval is specified so as to get accurate readings from the sensor and not overload it constantly, which might tamper the readings delivered by it.
6. Finally, the obtained temperature values are noted down and compared with the corresponding variation in load which led to its rise.
7. The temperature results obtained after the completion of the simulation were as follows -

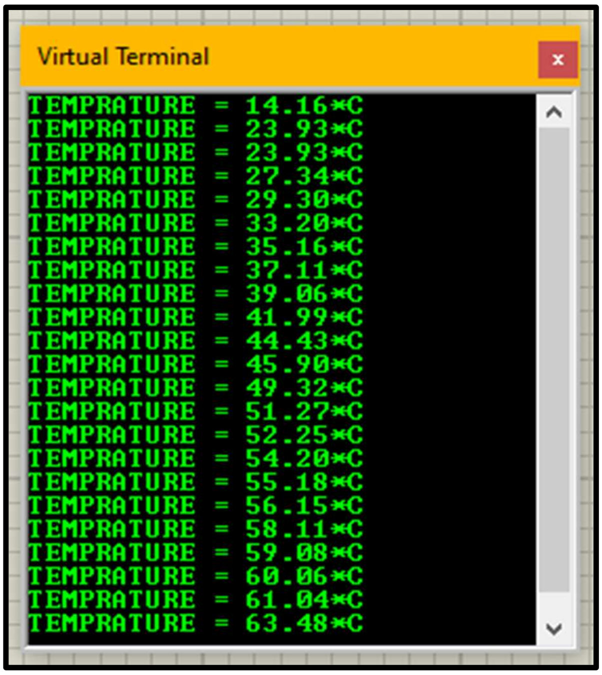

Fig. 6- The temperature readings obtained after the completion of the simulation

Table -2: Specifications of the designed transformer

Load Current (A)	Temperature (°C)	Secondary Voltage (V)
8.0	27.34	230
8.2	33.20	230
8.8	39.06	230
9.1	45.90	224
9.5	52.25	220
9.7	59.08	214
10.0	64.45	210

The results obtained clearly indicate that the rise in the windings of the transformer is extremely high, with temperatures as high as 65°C being recorded from the sensor. This implies that the process of overloading a transformer even as much as 40% more than its rated value can lead to temperatures rising 40-50°C more than the ambient temperature at which the transformer is placed at [5]. This can have a significant impact on the health of the transformer as such drastic rises in temperature can reduce the lifespan of the insulation material used within the transformer, as well as deteriorate the materials used within the transformer. This simulation can provide a vivid picture on the impact of temperature on a practical distribution transformer.

3. CONCLUSIONS

The preservation of the health of distribution transformers is a necessary action that needs to be looked into way more than the current-day scenario [6]. The ultimate denouement we hope to present through this paper is to provide a practically designed transformer, to demonstrate the overloading and heating effects observed within the transformer using modern-day software tools.

The simulation of the temperature rise occurring within the transformer provides us significant information on the impact of temperature hotspots forming within the transformer, which in turn inhibits the performance of the transformer and deteriorates the components within, thereby reducing the life span of the transformer. Overall, we aim to present a practically designed transformer capable of handling practical loads and to provide a picture on the adverse effects that heat has on the health of a distribution transformer.

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