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The Induction Motor; a Short Circuited Rotating Transformer – A Comparative Analysis

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Abstract: *With the advent of transformer, which encourages the atmost universal adoption of a.c system of transmission/distribution of electric energy, the field of application of induction motor has widened considerably in the recent years. Consequently, electrical machine manufacturers have endeavoured, over the years to perfect various types of a.c motors and transformers, suitable for all classes of domestic and industrial appliances and for both single and three phase a.c supply. As a.c electrical machines, transformers and induction motors share related/distinct characteristics. The idea of the induction motor seen as a generalized transformer is the object of our discussion.*

Keywords: *Air gaps, dynamic machine, electromagnetic induction, leakage reactance, magnetizing current, static machine.*

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I. Introduction

Electrical energy is generated by conversion of energy available in different forms from different natural sources, such as kinetic energy of the blowing winds, pressure head of water, chemical energy of fuel (either in solid, liquid or gaseous form) and nuclear energy of radio-active substances into electrical energy (J.B. Gupta 2008).

Presently, in West Africa with special references to Nigeria, most of the electric power for industrial and utility purposes is generated by large hydro-electric plants (as in kainji dam) and steam stations (as in Egbin) in the form of three phase a.c at a frequency of $50H_Z$. This energy generated is transmitted to a far distance at increased voltage and reduced current to the distribution centre while the voltage is reduced with a corresponding increase in current for the end users (consumers). This gives the implication that the generated power is transmitted twice, thrice or even four times before it is utilized.

All these activities of raising or lowering of a-c supply voltage is accomplished by transformers (A.K Sawhney 2008). Hence, electrical energy transformation from one level to another takes place in transformers.

The induction motor converts this transformed a-c voltage to mechanical energy. The transfer of energy from stator to the rotor of an induction motor takes place entirely inductively, with the help of a flux mutually linking the two. Unlike the transformer, the magnetic circuit of an induction motor has an air-gap (see fig 2). It is the length of air gap that primarily determines the magnetizing current drawn by the machine. The length of air gap affects the value of zig-zag leakage reactance which forms a large part of total leakage reactance of the motor. The magnetizing current in induction motor is much larger than that of transformer.

Additionally, in induction motor, the inputs to stator and rotor are electrical while the output from the rotor is mechanical, unlike in transformer where both input as well as output is electrical (V.K Mehta, R Mehta 2000)

Interestingly, the main difference between the induction motor and the transformer counterpart lies on the fact that in induction motor, the rotor voltage and its associated frequency are both slip dependent, unlike in transformer that is static.

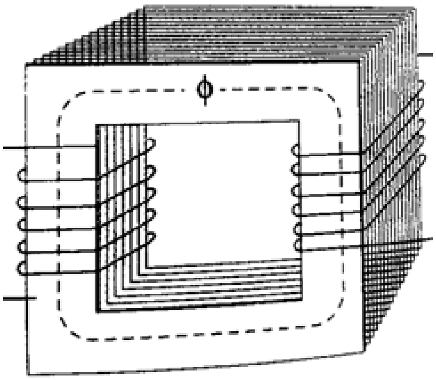

Plate 1: The Electric Transformer

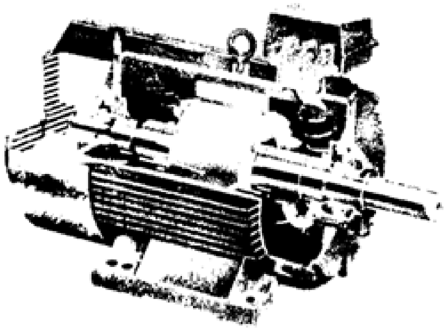

Plate 2: The Electric Motor

II. Analogous features of the equivalent circuits of the two machines

The equivalent circuits of all induction motors are similar to those of transformers, only that the rotors of induction motors rotate and mechanical power is developed.

Obviously, the stator windings of all induction motors are connected to supply mains and the rotor windings short circuited. The electrical energy is transformed from the stator winding to the short-circuited rotor winding by transformer action (Electromagnetic induction).

Hence, the induction motor is seen as transformer with a rotating short circuited secondary winding. The stator winding is an equivalent of the transformer primary and the rotor winding corresponds to transformer secondary. Owing to conditions of similarity of fluxes and voltages of the two a-c machines, one may expect a great similarity in the equivalent circuits of the two machines.

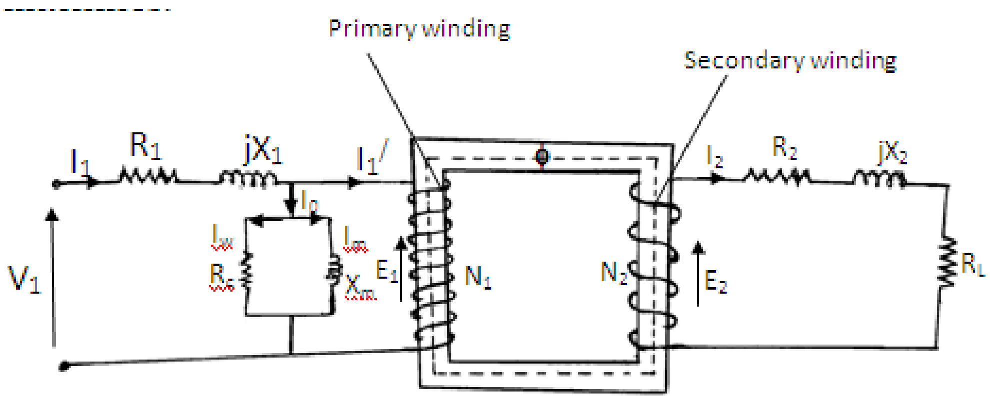

Fig. 1: Per-phase equivalent circuit of a transformer on load.

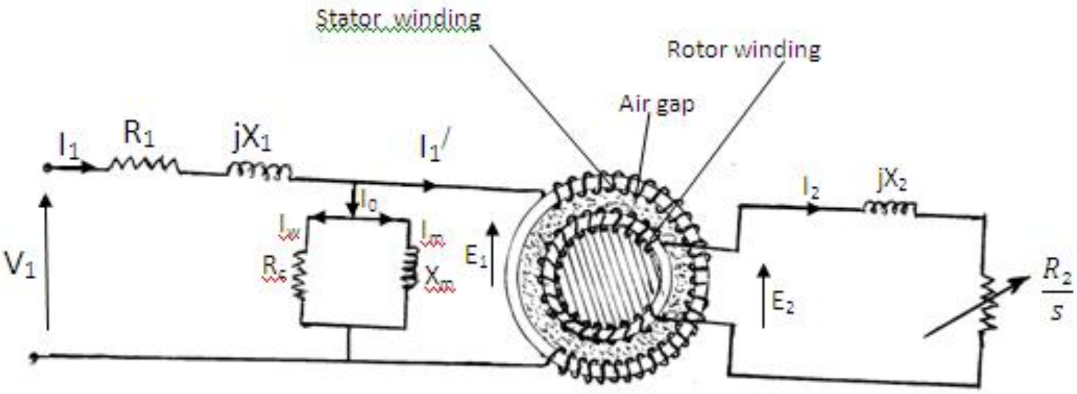

Fig 2: Per-phase equivalent circuit of an induction motor

In the stator circuit of figure 2, the events are similar to those in the transformer primary of figure 1. The applied voltage per phase to the stator is V_1, while R_1 and X_1 represent the stator resistance and leakage reactance per phase respectively.
The magnetic flux which links the primary (stator) winding as well as the secondary (rotor) winding are produced by V_1. When the transformer is at no load, the primary winding draws a no load current I_0. When losses are considered, then the no-load current I_0 is the phasor sum of two components Viz;
i. The magnetizing component (I_m) in phase with the flux
ii. The core-loss component (I_w) supplying the Hysterises and Eddy current losses. Hence the no load current is given by;

$$I_0 = \sqrt{I_m^2 + I_w^2} \qquad 1$$

The parallel combination of the core loss resistance (R_c) and magnetizing reactance (X_m) represents the no load losses and the production of magnetic flux respectively.
More-still, counter e.m.f.s are generated in the stator winding, owing to rotating air gap flux wave. The stator terminal voltage (applied voltage per phase), must overcome the counter e.m.f. If the counter e.m.f is $-E_1$. and the stator leakage impedance drop is $I_1(R_1+jX_1)$, then the stator terminal voltage (V_1) yields;

$$V_1 = -E_1 + I_1\,(R + jX_1) \qquad 2$$

$$I_1 = I_1^{/} + I_0 \qquad 3$$

Where I_1 is the stator current and $I_1^{/}$ is the load component and counteracts the rotor mmf.
In induction motor, I_0 supplies the resultant air gap flux ($\emptyset$) and no load losses (core loss + friction + windage loss + small stator and rotor I^2R loss). But in transformer, I_0 supplies core loss only. Therefore I_0 is not called no-load current in induction motor as it is called in transformers (Smarajit Ghosh 2007). The Product $-E_1I_w$ in a three phase induction motor gives the core less per phase.
In the rotor circuit of figure 2, the events are almost entirely different from those in the transformer secondary of figure 1. Here R_2 and X_2 represent the secondary (rotor) resistance per phase respectively. At varying slip s, the rotor reactance changes, so that the per phase rotor current yields;

$$I_2 = \frac{E_2}{\frac{R_2}{S} + jX_2} \qquad 4$$

When an induction motor is stationary (at stand still), the stator and rotor windings form the equivalent of a transformer as in figure 1 (with R_2 short-circuited). Hence, equation 4 becomes;

$$I_2 = \frac{E_2}{R_2 + jX_2} \qquad 5$$

The rotor e.m.f (E_2) becomes;

$$E_2 = \left(\frac{N2}{N1}\right) E_1 \quad (transformer\ equation) \qquad 6$$

When the induction motor is running, the induced e.m.f in the rotor is less since the relative movement between conductors and rotating field is less. The induced e.m.f is proportional to this movement, hence it must be proportional to the slip(s) (John Bird 2010). Hence when running, rotor e.m.f per phase is given by;

$$E_r = sE_2 = s\left(\frac{N2}{N1}\right) E_1 \qquad 7$$

III. Transformer Equivalent Circuit of Induction Motor

The merging of the transformer and the induction motor equivalent circuits of fig 1 and 2 gives the transformer equivalent circuit of induction motor. In such combination, one must be aware that the input to the primary and output from the secondary of a transformer is electrical. In an induction motor, the inputs to the stator and rotor are electrical, but the output from the rotor is mechanical. Hence it becomes imperative to replace the mechanical load $\frac{R_2}{s}$ by an equivalent electrical load (R_L). This brings about the transformer equivalent circuit of the induction motor of figure 3.

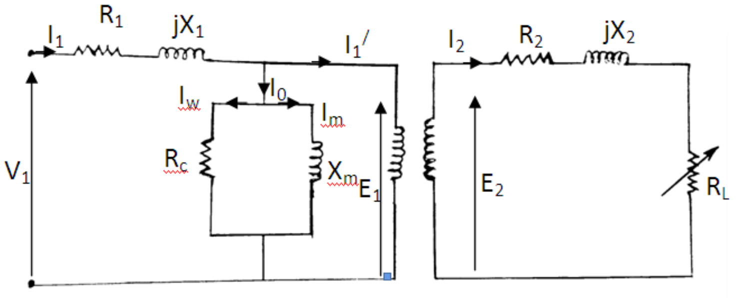

Fig 3-Per phase transformer equivalent circuit of a 3 phase induction motor with load resistance (R_L).

Refer to figure 2, at the rotor side, we have a rotor circuit that has a fixed reactance X_2 connected in series with a variable resistance $\frac{R_2}{S}$ and supplied with constant voltage E_2. The quantity $\frac{R_2}{s}$ is greater than R_2 of figure 1, since s is a fraction with range of values 0≤s<1 (for induction motor operation on run condition). The variable resistance $\frac{R_2}{s}$ can be divided into a fixed part R_2 and variable part $(\frac{R_2}{s} - R_2)$.

So that $\frac{R_2}{s} = R_2 + (\frac{R_2}{s} - R_2)$

$= R_2 + \frac{R_2}{s}$ (1-s) 8

From equation 8,

i. The first part R_2 is the rotor resistance per phase and represents the rotor copper (cu) loss

ii. The second part $\frac{R_2}{s}$ (1-s) is a variable resistance load. The power delivered to this load represents the total mechanical power (P_m) developed in the rotor.

This is a validation of figure 2 and figure 3 where the variable mechanical load $(\frac{R_2}{s})$ on the induction motor is now replaced by a variable resistance load (R_L) of value $\frac{R_2}{S}$ (1-s). This is known as electrical load resistance (R_L) or the electrical analogue of the variable mechanical load $(\frac{R_2}{s})$.

Hence, the electrical load resistance $(R_L) = \frac{R_2}{s}$ (1-s) = $R_2 (\frac{1}{s} - 1)$ 9

Excitingly, from equations 8 and 9, for slip(s) = 1, the variable resistance $(\frac{R_2}{s})$ equals the rotor resistance (R_2), as electrical load resistance (R_L) equals to zero. In an electric circuit, terminals of a zero resistance value imply an infinite (maximum) current flow between the terminals. Hence, figure 3 becomes the equivalent circuit of a short-circuited two winding transformer.

Similarly, for slip(s) = 0, the variable resistance $\frac{R_2}{S}$ becomes infinite, just as the electrical load resistance (R_L) is infinity too. In an electric circuit, terminals of an infinite resistance value implies a zero (no) current flow between the terminals. Hence figure 3 is seen as the equivalent circuit of an open-circuited transformer.

IV. Conclusion

It is obvious that transformer and induction motors share related features both in their principles of operations and their equivalent circuits. Distinctively, in transformers, the approximate equivalent circuit is obtained by referring the parallel branch across the primary sides. This is because the no-load current (I_0) is between 3% to 5% full-load current (I_F). Also, the per unit leakage reactance is low. Unlike the transformer, for the induction motors, the no load current is between 25%-50% of full load with a corresponding high per unit leakage reactance. To this effect, if the parallel branch is referred to the stator side, considerable error will be introduced.

However, core losses in induction motors are usually constant, especially during normal operating condition. Owing to this condition, the core loss resistance R_C representing the motor core loss can be neglected, so that the parallel part of the equivalent circuit of figure 3 has only the magnetizing reactance (X_m).

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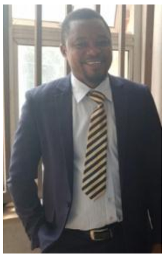

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