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RESEARCH ARTICLE

PHYSICAL CONFIGURATION AND PRINCIPLE OF OPERATION OF A TRANSFER FIELD MACHINE (TFM) AND AN INDUCTION MACHINE (IM): A COMPARATIVE ANALYSIS

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ABSTRACT

This paper presents a comparative analysis of a transfer field machine (TFM) and a poly-phase induction machine (IM) with main focus on physical configuration and principle of operation . It is shown in the analysis that although the two machines belong to two different classes of machine and quite different in physical configuration , yet in their principle of operation , the induced electromotive force (e. m. f) as well as the frequency of this induced e. m. f in both the auxiliary winding of the transfer field machine and the rotor of an induction machine , is proportional to slip. And even though the TFM does not have rotor windings, it is also very obvious from the analysis that the auxiliary winding , is playing the role of the rotor winding compared to an IM. The TFM, produces a reluctance torque as a result of the auxiliary (rotor) pole -axis trying to align with the axis of maximum flux . But that of IM, is by alignment of fields ,that is, the rotating magnetic field of the rotor trying to catch up with that of the stator.

INTRODUCTION

The theory of induction machine is old and well known. An induction machine consists essentially of two major parts, the stator and the rotor. When an a.c voltage is impressed on the terminals of the stator windings, a rotating magnetic field is set up. This rotating magnetic field produces an electromotive force (e.m.f) in the rotor by electromagnetic induction (transformer action) which in turn, circulates current in the rotor usually short-circuited. This current circulating in the short-circuited rotor, produces a rotating magnetic field which now interact with the rotating magnetic field already established in the stator. This interaction produces a torque which is responsible for the rotation of the machine. Induction machine is also known as the asynchronous machine which derives from the fact that the rotor magnetic field is always lagging the stator magnetic field. The difference is called the slip, and it is a fundamental characteristic in the operation of an induction machine. An induction machine when it operates below synchronous speed, is a motor while it is a generator when it operates above the synchronous speed. In fact induction machines are mostly used as motors.

The induction motor is used in a wide variety of applications as a means of converting electric power to mechanical work. It is without doubt, the workhorse of the electric power industry. Pump, steel - mill and hoist drives are but few applications of large multiphase induction motors. On a smaller scale, the single-phase servo motor is used extensively in position-follow-up control systems and single – phase induction motors are widely used in household appliances as well as hand and bench tools [1]. The transfer-field (TF) machine is structurally basically a reluctance machine. It differs however from the simple reluctance machine in two important respects namely:-

- It has two sets of windings instead of one
- Each winding has a synchronous reactance which is independent of rotor position whereas the winding reactance of a single reluctance machine varies cyclically [2].

The TF machine configuration has two stator windings in each machine element known as main and auxiliary windings. The main windings are connected in series while the auxiliary windings are connected in series but transposed between the two machine sections. There are no windings on the rotors of either of the composite machines.

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This machine induces negative sequence emfs of frequency $(2S - 1)\omega_o$ in the auxiliary windings which will in turn circulate a current excluded from the supply. The interaction of the main and auxiliary winding magnetomotive forces (mmfs), will produce an interference wave with beat frequency, ω, which is equal to the rotor frequency. Hence a reluctance torque is developed in the rotor as a result of its interaction with the interference wave and this causes the rotor and hence the machine to rotate (turn). And so a transfer-field machine is an energy converter and like the induction machine, is asynchronous and self starting. The transfer – field machine is very useful in control systems, electrical gear, low speed drives etc. Again its auxiliary winding terminals which will act as the rotor conductors in normal induction machine is available without requiring slip rings or current collection gears. It can also be used to supply a d.c load through rectifiers, a function which has not been performed satisfactorily by induction motors because the output waveforms of induction motors tends to be increasingly distorted as the load current increases. Also it is capable of survival in a harsh environment [3]. In this paper, a comparative analysis of the transfer-field machine (TFM) and induction machine (IM) is carried out. The comparative analysis is focused on the physical configuration and principle of operation.

Physical Configuration of a Transfer Field Machine (TFM): The transfer field machine (TFM) comprises a two stack machine in which the rotor is made up of two identical equal halves whose pole axes are $\frac{\pi}{2}$ radians out of phase in space. They are housed in their respective induction motor type stators. There are no windings in the rotor. The stator has two physically isolated but magnetically coupled identical windings known as the main and auxiliary windings. The axes of the main windings are the same in both halves of the machine whereas the axes of the auxiliary windings are transposed in passing from one half of the machine to the other. Both sets of winding are distributed in the stator slots and occupy the same slots for perfect coupling and have the same number of poles. The two sets of winding of the transfer field machine are essentially similar and may be connected in parallel which will of course double its output.

The schematic diagram of a transfer field machine (TFM) is as illustrated in figure below:

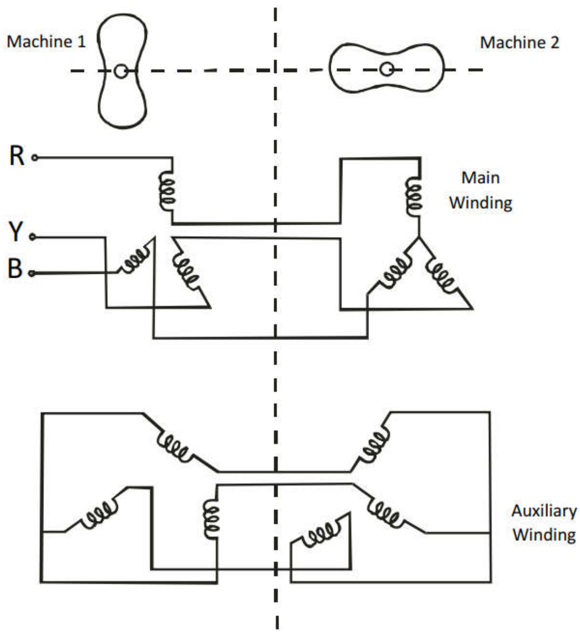


Fig.1.0. Connection diagram for a transfer field machine (TFM)

Principle of operation of a TFM:

In its principle of operation, when the main winding of machine 1 is connected to an a.c supply voltage, V_1 , with the auxiliary windings open circuited, it draws a magnetizing current, I_1, at a supply or source frequency, ω_0. And this magnetizing current produces an mmf distribution on both elements of the machine (i.e m/c_1 and m/c_2).

Let this magnetizing mmf in machine 1 be given by;

$$m_1 = Mo \cos (x - \omega_0 t) \quad (1)$$

where;

ω_0 =supply (source) frequency.

Mo =excitation mmf

The permeance distribution in the rotor is given by;

$$Pe = a + b\cos 2(x - \omega t) . \qquad (2)$$

Where; ω is the rotor speed.

The flux density distribution in machine 1 due to excitation mmf, m_o, is given by;

$$B_1 = m_1 Pe = M_o \cos(x - \omega_o t)\,[a + b\cos 2(x - \omega t)] \qquad (3)$$

$$B_1 = aM_o\cos(x - \omega_o t) + M_o b\cos(x - \omega_o t)\cos 2(x - \omega t) \qquad (4)$$

Simplification of equation (4), gives that;

$$B_1 = aM_o\cos(x - \omega_o t) + M_o b\,\{\tfrac{1}{2}[\cos\{x + (\omega_o - 2\omega)t\}] + \underbrace{\tfrac{1}{2}[\cos\{3x - (\omega_o + 2\omega)t\}]\}}_{3^{rd}\text{ space harmonics}} \qquad (5)$$

This flux density rotates in the positive anti-clockwise direction.

On the second half of the machine (i.e machine 2), the magnetizing mmf is;

$$m_2 = M_o\cos(x - \omega_o t) \qquad (6)$$

and the pemeance distribution of the air gap of the rotor is given by;

$$P_e = a + b\cos 2(x - \omega t - 90^0)$$

$$= a + b\cos\{(2x - 2\omega t) - 180^0\}$$

The simplification of the above expression, gives;

$$Pe = a - b\cos(2x - 2\omega t) \qquad (7)$$

Comparing equations (2) and (7), it is deduced that flux density distribution in machine 2 is;

$$B_2 = M_o\cos(x - \omega_o t)\{a - b\cos 2(x - \omega t)\} = aM_o\cos(x - \omega_o t) - M_o b\cos(x - \omega_o t)\cos 2(x - \omega t)$$

$$B_2 = aM_o\cos(x - \omega_o t) - Mob\,\underbrace{\{\tfrac{1}{2}[\cos\{x + (\omega_o - 2\omega)t\}] + \tfrac{1}{2}[}_{3^{rd}\text{ space harmonics}}\cos\{3x - (\omega_o + 2\omega)t\}]\} \qquad (8)$$

In both equations (5) and (8), the third space harmonics are eliminated because the machine is star-connected. As depicted from equations (5) and (8), the flux densities for machine 1 and machine 2 with the third harmonics neglected are given by;

$$\underset{\substack{\downarrow \\ e_o}}{B_1 = aM_o\cos(x - \omega_o t)} + \frac{M_o b}{2}\cos\underset{\substack{\downarrow \\ e_2}}{\{x + (\omega_o - 2\omega)t\}} \qquad (9)$$

[5] Equation (10) should be properly typed as,

$$\underset{\substack{\downarrow \\ e_o}}{B_2 = aM_o\cos(x - \omega_o t)} - \frac{M_o b}{2}\cos\underset{\substack{\downarrow \\ e_2}}{\{x + (\omega_o - 2\omega)t\}} \qquad (10)$$

The first components of equations (9) and (10), will induce emfs, e_o, in the main windings which is additive and tend to oppose the voltage supply. The emfs they induce in the auxiliary windings cancel out. These emfs are equal in magnitude and in time phase. The second components of equations (9) and (10), will induce voltages, e_2, in the main windings which are equal and opposite and in consequence, cancel each other (anti phase).However in the auxiliary winding, these induced voltages, e_2, will add up because of the transposition of the auxiliary windings. This is as illustrated in Figure 2.

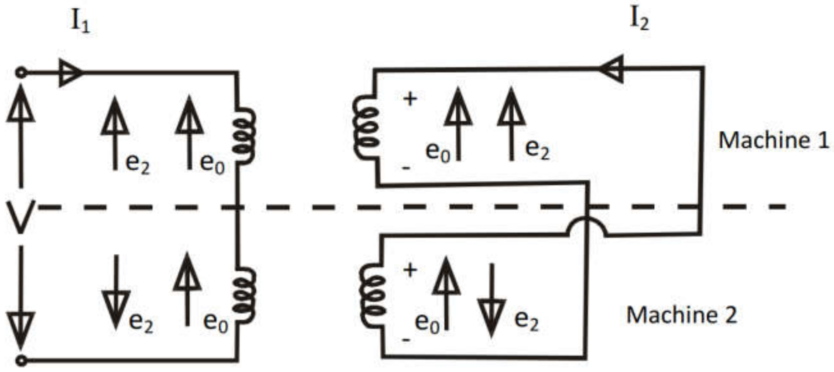


Fig. 2. Induced voltages, e_o, e_2 in the main and auxiliary windings

The average flux density linking the main winding is obtained by addition of equations (9) and (10) and is given by;

B_{av}(main) $= \frac{1}{2}(B_1 + B_2) = aM_o\cos(x - \omega_o t)$ (11)

And this average flux density, B_{av}(main), produces an induced voltage of magnitude $2e_o$. The average flux density in the auxiliary winding is obtained by subtracting equation (10) from Eqn (9) and this gives;

B_{av}(aux.) $= B_1 - B_2 = Mob\cos\{x + (\omega_o - 2\omega)t\}$ (12)

The frequency of the induced voltages and currents in the auxiliary winding rotate in opposite direction to the magnetizing mmf; and this frequency is given by $(\omega_o - 2\omega)$.

But $\dfrac{\omega_0 - \omega}{\omega_0} = s$

This implies that $\omega = \omega_o(1 - s)$

Therefore the induced emf in the auxiliary winding may be expressed as;

$e_2 = M_o b\cos[x + \{\omega_o t - 2[\omega_o(1 - s)]t\}]$
$= M_o b\cos[x + \omega_o t - 2\omega_o t + 2\omega_o st]$
$= M_o b\cos[x - \omega_o t + 2\omega_o st]$
$e_2 = M_o b\cos[x + (2s - 1)\omega_o t]$ (13)

This induced emf in the auxiliary winding will circulate current in the auxiliary winding circuit when it is short circuited and this current is given by:

$$I_2 = \frac{e_2}{R + j(2s-1)\omega_O L}$$

$$I_2 = \frac{e_2}{R + j(\omega_O - 2\omega)L}$$
$$= \frac{e_2}{\sqrt{R^2 + \{(\omega_0 - 2\omega)L\}^2}\tan^{-1}\left[\frac{(\omega_0 - 2\omega)L}{R}\right]}$$

Let the impedance angle be ϕ

$$\Rightarrow I_2 = \frac{e_2}{\sqrt{R^2 + \{(\omega_0 - 2\omega)L\}^2}\angle\emptyset} \quad (14)$$

Where $\phi = \tan^{-1}\dfrac{(\omega_0 - 2\omega)L}{R}$ (15)

The current, I_2, produces mmf distribution which may be expressed as;

$m_2 = \pm M_2\cos\{x + (\omega_o - 2\omega)t - \lambda\}$ (16)

If the mmf distribution in machine 1 is given by;

$B_1^/$ = -M$_2$ cos $\{x+(\omega_0-2\omega)t-\lambda\}[a-b\cos 2(x-\omega t)]$, and in machine 2, it is;

$B_2^/$ = M$_2$ cos $\{x+(\omega_0-2\omega)t+\lambda\}[a-b\cos 2(x-\omega t)]$, then the resultant mmf in machine 1 is given by;

$mmf_{R1}=M_1\cos(x-\omega_o t-\sigma)+M_2\cos\{x+(\omega_o-2\omega)t-\lambda\}$ (17)

But $M_1 = \pm M_2$ in magnitude at equilibrium. Therefore the resultant mmf in machine 1 is;

$mmf_{RM/C\,1}= M_2\cos(x-\omega_o t-\sigma)+M_2\cos\{x+(\omega_o-2\omega)t-\lambda\}$

$= M_2\cos(x-\omega_o t-\sigma)+M_2\cos\{x+\omega_o t-2_{\omega t}-\lambda\}$

Now letting $C = x + \omega_o - 2\omega t - \lambda$ & $D = x - \omega_o t - \sigma$

and applying the trigonometrical expression that ;

$\cos C + \cos D = 2\cos\frac{C+D}{2}\cos\frac{C-D}{2}$, gives the final value of $mmf_{RM\backslash C1}$ as;

$mmf_{RM/C\,1}=\frac{M_2}{2}\cos\{(\omega_o-\omega)t+(\frac{\alpha-\lambda}{2})\}\cos\{x-\omega t-(\frac{\alpha+\lambda}{2})\}$ (18)

Equation (18) is an mmf wave rotating at the speed of the rotor, ω, but amplitude modulated by $\frac{M_2}{2}\cos\{(\omega_o-\omega)t+\frac{\alpha-\lambda}{2}\}$
The resultant mmf in machine 2 is given by the expression;

$mmf_{RM/C\,2}= M_2\cos(x-\omega_o t-\sigma)-M_2\cos\{x+(\omega_o-2\omega)t-\lambda\}$

$= M_2\cos(x-\omega_o t-\sigma)-M_2\cos(x+\omega_o t-2\omega t-\lambda)$

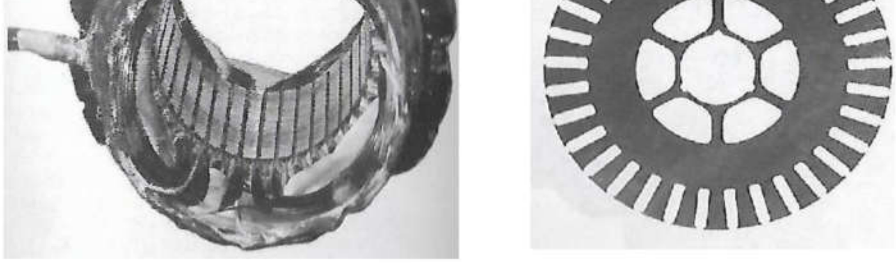
In a similar manner as before, applying the trigonometrical expression that;

$\cos D - \cos C = 2\sin\frac{C+D}{2}\sin\frac{C-D}{2}$ into the above expression for $mmf_{RM\backslash C2}$ and simplifying, gives the final value of $mmf_{RM\backslash C2}$ as;

$mmf_{RM\backslash C\,2}=\frac{M_2}{2}\sin\{(\omega_o-\omega)t+(\frac{\alpha-\lambda}{2})\}\sin\{x-\omega t-(\frac{\alpha+\lambda}{2})\}$ (19)

Similarly, equation (19) is an mmf wave rotating at the speed of the rotor ,ω, but amplitude modulated by $\frac{M_2}{2}\sin\{(\omega_o-\omega)t+\frac{\alpha-\lambda}{2}\}$
Now the mmf produced by the primary (main) winding due to current, I_1, is given by; $m_{1M/\backslash C1} = m_{1M/\backslash C2} = M_1\cos(x-\omega_o t-\sigma)$
Therefore the interaction of the main and auxiliary winding mmfs will produce a reluctance torque which causes the transfer field machine to turn.

Physical configuration of an Induction Machine (IM): The induction machine comprises a stator and a rotor mounted on bearings and separated from the stator by air-gap. The stator consists of a magnetic core made up of laminations carrying slot-embedded conductors which constitute the stator windings. The rotor of induction motor is cylindrical and carries either conducting bars short-circuited at both ends by end rings (squirrel cage rotor) or a polyphase winding connected in a predetermined manner with terminals brought out of slip rings for external connections and short circuited. A close-up view of stator and rotor of an induction machine is shown in Figure 3.



(a) Stator Core and Coil Assembly (b) Rotor Lamination showing Slots for bars of the Squirrel-cage winding

Fig. 3. A close-up view of stator and Rotor of an IM [3]

The winding arrangement of a typical 2-pole, 3-phase, star-connected, symmetrical induction machine is as shown in figure 4.

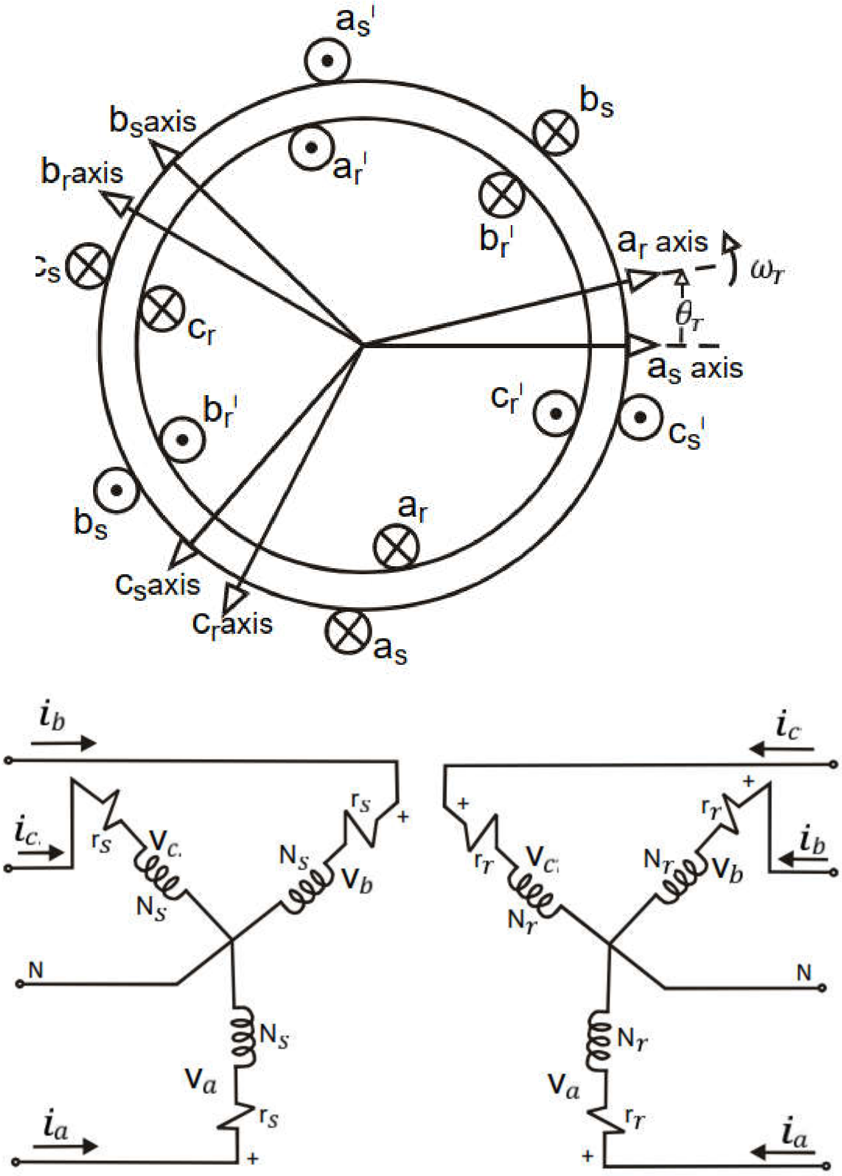


Fig. 4.Two-pole, 3-phase, star-connected, symmetrical induction machine

Principle of operation of an IM: The basic idea behind the operation of an induction machine is quite simple. In this paper, qualitative description of the principles of operation is adopted. A poly phase induction machine such as the one provided in figure (3), consists essentially of two major parts namely the stator and the rotor. When the three phase stator winding as depicted in figure 4, is excited with a.c voltage, currents flow in the stator winding setting up a rotating mmf and flux density. This stator flux density rotates at synchronous speed given as;

$$n_s = \frac{120 f_e}{p_n} \text{ rpm} \tag{20}$$

n_s= Synchronous speed in revolution per minute (rpm).
f_e= Supply frequency in Hertz
p_n= Number of poles.

This rotating field established in the stator winding induces an emf in the rotor winding by transformer action and this induced voltage will cause current to circulate in the rotor winding if it is short-circuited. This current flowing in the short-circuited rotor produces magnetic field in the rotor and this rotor magnetic field acts to oppose the stator magnetic field and also rotates at synchronous speed. It is the interaction of these two magnetic fields rotating at constant speed that produces a torque which is responsible for the rotation of the machine [1]. The rotor flux density will lag the stator flux density (flux density lags current by

90^0 electrically), therefore the torque will be in the same direction as rotation of the magnetic fields. This torque induced, accelerates the rotor until synchronous speed is reached at which time there is no relative motion between the conductors and the stator flux density. At this instant, the relative velocity between the stator and the rotor is zero and consequently the induced voltage, rotor currents and flux density fall to zero and the torque is also zero.

IM Induced Rotor Voltage: From the fundamental theory on rotating fields, passing balanced three-phase currents through a balanced three-phase winding can produce a rotating mmf wave. Speed of rotation is set by supply frequency and the number of poles in the machine. In an induction machine, the air-gap of the machine is designed to be constant, therefore the rotating mmf will produce a rotating flux density. The stator flux density can be defined in terms of either mechanical or electrical quantities as [5];

$$B_s = B_s \cos\left[\frac{P}{2}(\theta_m + \phi_m - \omega_s t)\right] = B_s Cos[(\theta_e + \phi_e - \omega_e t)] \quad (21)$$

In the above equation, ϕ_m and ϕ_e are arbitrary phase angles in mechanical and electrical angles respectively. They are normally set to zero. θ is the location at which the flux density waveform is observed. At a given location, the flux density varies sinusoidally with time and at a given time, it varies sinusoidally with location. Let us consider the flux density seen by a conductor on the rotor.

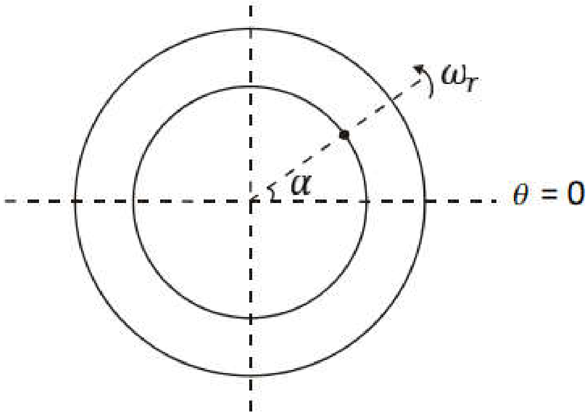


Fig.4. Image of a rotating mmf wave.

In the image of a rotating mmf wave shown above, there is a rotor conductor at position $\theta_m = \alpha$. If the rotor is stationary, then the rotor will observe the stator flux density as ;

$$B_s = B_s \cos\left[\frac{p_n}{2}(\alpha - \omega_s t)\right] \quad (22)$$

However, if the rotor is rotating at mechanical speed, ω_m, the location of the conductor becomes;

$$\theta_m = \alpha + \omega_m t \quad (23)$$

and the flux density seen by the conductor is given by;

$$\mathbf{B_s} = B_s \cos\left[\frac{p_n}{2}\{\alpha + (\omega_m - \omega_s)t\}\right]$$

$$= B_s \cos\left[\frac{p_n}{2}(\alpha - s\omega_s t)\right]$$

$$= Bs \cos\left[\frac{p_n}{2}\alpha - \frac{p_n}{2} s w_s\, t\right]$$

$$= B_s \cos\left[\frac{p_n}{2}\alpha - s\omega_e t\right] = B_s \cos\left[\frac{p_n}{2}\alpha - \omega_{sl} t\right] \quad (24)$$

where;

P_n = number of poles

ω_e = supply frequency in rads^{-1}

$\omega_{sl} = s\omega_e$ = slip frequency in rads^{-1}

Now the voltage induced in a conductor of length, l, moving with velocity, U, perpendicular to a magnetic field is given by [6];

$$e = Blu \tag{25}$$

and the relative velocity of the conductor through the magnetic field is given by;

$$U = r\omega_{sl} = sr\omega_e \tag{26}$$

Therefore the voltage induced in the rotor conductor is obtained by substituting equations (24) and (26) into equation (25) which gives;

$$e = srl\omega_e B_s \cos\left[\frac{p_n}{2}\alpha - sw_e\, t\right] \tag{27}$$

IM Rotor Current and Field: Without knowing the full details of the rotor circuit, we can make some assumptions about the circuit to enable us to understand the behavior of the induction machine. The assumption is that the rotor conductor is part of a circuit with constant resistance R_R and inductance, L_R [5]. Now if the slip is low ($s \to 0$), then the reactance associated with the inductance will be negligible and is given by the expression;

$$X_R = s\omega_e L_R. \tag{28}$$

In this case, though induced voltage is small, the induced current may be significant since the conductors are short – circuited, and so, R_R is low. Also the currents will be approximately in phase with the induced voltage. If the slip is high ($s \to 1$), then the rotor reactance will be significant and due to the increase in induced voltage, rotor currents will be high but will lag the induced voltage significantly due to the inductance of the rotor .

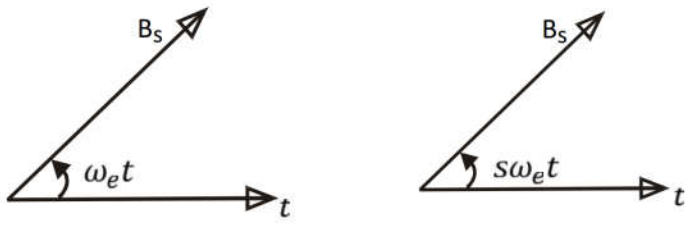
The flux density produced by a set of a.c. currents rotates at a speed given by;

$$n_s = \frac{120 f_e}{p_n}\ \text{rpm} \tag{29}$$

In the case of rotor currents, equation (29), gives the speed of rotation relative to the conductors. However the actual speed of rotation of the flux density will be given by;

$$\omega_r = \omega_s(1-s)\ \text{rad/sec} \tag{30}$$

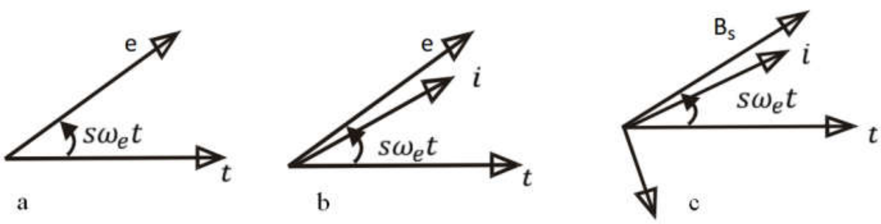
That is, the rotor magnetic field rotates at synchronous speed. We can get an understanding of the relative position of the rotor and stator fields by drawing phasor diagrams. The phasor diagram of the stator flux density can be drawn from either a stator reference frame where it rotates at electrical speed, ω_e or from the rotor reference frame, where it rotates at electrical speed $s\omega_e$



(a) Stator phasor observed from stator (b) Stator phasor observed from rotor

Fig. 5. Stator phasor observed from stator and rotor

We first consider the case where slip, S, is low. In this case, induced current lags induced voltage slightly while the rotor flux density is almost 90^0 electrically behind the stator flux density. This is as illustrated in figure 6.



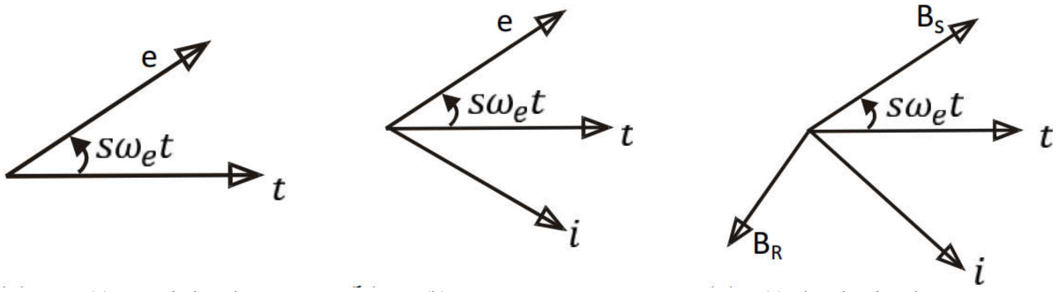
Rotor induced voltage at low slip

Rotor current at low slip

Flux density phasors observed from rotor at low slip

Fig. 6. Phasors for rotor induced voltage, current and flux density at low slip

From figure (6), it is seen that at low slips, the angle between the flux density phasors is close to 90^0 and from $\tau = K_i B_R \times B_s$, it is very clear that the torque will be approximately proportional to induced voltage and therefore proportional to slip. Now when the slip is very high (i.e.; close to 1.0), mechanical speed is close to zero. In this case, rotor current lags induced voltage and the angle between rotor and stator flux densities is much greater. This is as illustrated in figure 7.



(a) Rotor induced voltage at high slip

(b) Rotor current at high slip

(c) Flux density phasors observed from rotor at high slip.

Fig. 7. Phasors for rotor induced voltage, current and flux density at high slip

From the torque equation, even though the magnitude of the induced currents is higher and the rotor flux density phasor has a high magnitude, torque will not necessarily be higher than it is at low slips [7].

Conclusion

From the physical configuration and principle of operation of the two machines considered, one can conclude that;

1. The TFM and IM have physical configuration that greatly differed . From the physical configuration, it is seen that;
(a) For the TFM, the stator and rotor are arranged in two identical coupled halves while for the IM, both stator and rotor are mounted on bearings and separated from each other by air-gap.
(b) For the TFM, the rotor has no conductor windings and the pole axes of the two rotor halves are mutually in space quadrature while the rotor of an IM, has conductor windings.
2. It is very evident that the induced voltage in both the auxiliary winding of TFM and rotor of IM ,is proportional to slip. This is as depicted in equation (13) for TFM and equation (27) for IM.
3. From the same equations for the induced voltage in the auxiliary winding of TFM and rotor of IM, it is also clear that the frequency of the induced voltage is proportional to slip.
4. Even though the TFM does not have rotor windings, it is obvious that the auxiliary winding is playing the role of the rotor winding compared to an IM.
5. It is also very evident from the principle of operation that TFM, produces reluctance torque as a result of the auxiliary (rotor) pole-axis trying to align with the axis of maximum flux. But that of IM, is by alignment of fields, that is, the rotating magnetic field of the rotor trying to catch up with that of the stator.

It is hoped that these identical characteristics including those not covered in this paper such as similar torque – slip characteristics of the TFM with IM , should be harnessed to design and construct more robust transfer field machines as this will increase its industrial acceptance as well as augmenting the role of IM as the workhorse of the electric power industry.

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