IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 15, Issue 3 Ser. II (May – June 2020), PP 15-23
www.iosrjournals.org

Imperatives of Air-Gap Length on the Performance of Electromechanical Devices/Machines

Anazia E.A.[1], Obute K. C.[2], Olufolahan Oduyemi[3], Eze E.C[4]
1,2.Department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria.
3.Department of Engineering and Technology, South East Missouri State University, Cape Giradeau, Missouri MO63701, USA
4.Department of Electronic and computer Engineering, Nnamdi Azikiwe University, Awka, Anambra State Nigeria.
Corresponding author: Obute Kingsley Chibueze
Department of Electrical Engineering, Nnaamdi Azikiwe University Awka

Abstract: *The goal of this study is to X-ray the imperativeness of air gap length on the performance of linear electromechanical devices (such as relays, electric door bells etc) and rotating electromechanical machines (such as generators and motors). Performance like power factor, magnetizing current, leakage reactance, overload capacity, unbalanced magnetic pull, cooling and noise etc. are greatly influenced by machine air gap length. Large or small air gap lengths in electromechanical devices/machines have desiring as well as devastating effects on them. As air gap is one of the concerns for designing any type of electrical system, a balance between the two extremes becomes the engineer's target and desire during such design.*

Key words: *Air gap, air gap length, air gap flux, electromechanical, magnetizing current.*

Date of Submission: 01-06-2020 Date of Acceptance: 16-06-2020

I. Introduction

One of the most desirable requirements for energy conversion from electrical energy to mechanical energy or vice-versa is the existence of magnetic field as a medium where relative motion is possible between the stator (stationary component of a rotating machine) and the rotor (the movable component).

The medium used is a "free open space", which physically separates the two machine components, and is known as air gap, while the distance between the two positions is the air gap length.

Air gap is the clearance between the rotor and the stator part of a machine. This minimum clearance needed to be maintained by a moving object, to freely move uninterrupted as it rotates on itsaxis or translates along its path. Obviously, in rotating machines, air gap is usually present, yet unavoidable. This is due to the necessity of physical movement required between the stator and the rotor. In the air gap, the rotating magnetic field rotates at synchronous speed and hence the rotor follows. All energy conversion process takes place in the air gap. Without the air gap, the field won't develop. Unlike in rotating machines, the existence of air gap between the core (fixed part) and the armature (movable part) of electromechanical devices is necessary, for smooth linear movements between the two component parts.

In the design of magnetic circuits of various electrical machines, the aim is to achieve a reasonable high flux in various parts of the circuit with no impending losses. For all electromechanical devices/machines, the magnetic circuit calculations largely depend on the relationship between magnetomotive force (mmf) and magnetic flux in various magnetic parts of the circuit and the air gap length. For a given value of mmf, the total flux depends on the reluctance of the individual magnetic parts [1].

The magnetic parts of all electromechanical devices/machines are made of ferromagnetic materials, so that their magnetic resistances are negligible compared with the reluctances in their air gaps. Hence almost all the linkage flux (mmf) in the magnetic circuit is utilized to set up the needed magnetic flux in the air gap.

II. Effect of Air gap length on the performance of induction motor

The induction motors are the "transformer type" a.c in which electrical energy is converted to mechanics energy. The induction motors consist of stator which is a stationary part, fixed to the yoke of the machine and rotor, a rotating part and free to rotate. Stator and Rotor are the two prime parts of any electromechanical machine. These are two electromagnets and are magnetically coupled and power is transferred from either side depending upon the machine through the magnetic field set up. Slots are provided on both stator and rotor, and winding wires are housed in these slots [2]. In between the stator and the rotor arrangement is a clearance (air gap), whose length determines principally its performance. Performance like harmonic torque, power factor, magnetizing and no load current etc. are affected by the length of air gap.

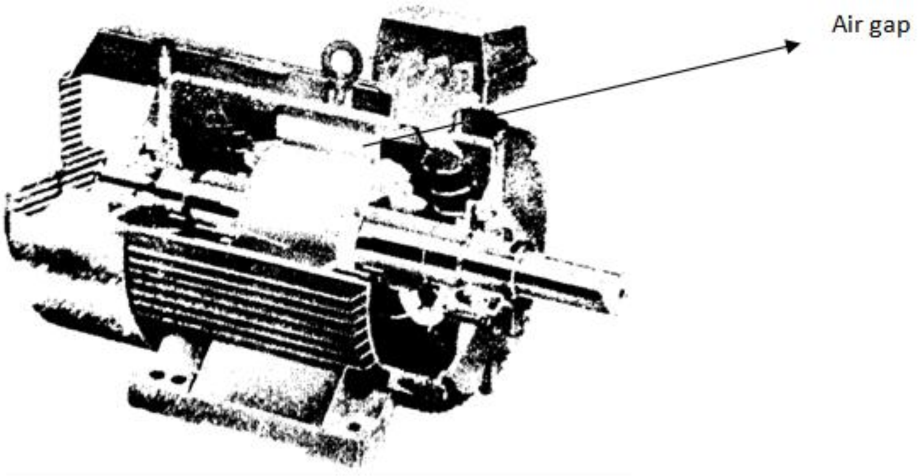


FIG. 1: The Induction Motor showing air gap [3]

The merits and demerits of providing a larger air gap in induction motor include;

Merits

i. Better overload capacity of the motor
ii. Reduction in noise, as zig-zag leakage flux is reduced
iii. Reduction in unbalanced magnetic pull and tooth pulsation losses
iv. Improved cooling, due to increased distance between cylindrical surfaces of stator and rotor

Demerits

i. Increased magnetizing current-The amount of magnetizing current drawn by the rotor depends on the length of air gap, hence, total ampere turns (mmf) required to overcome the reluctance of air gap is directly proportional to the length of air gap.

ii. Reduced power factor- The operating power factor is lesser for motors which draw higher magnetizing currents. This poor power factor causes flow of more reactive current from the mains into the motor, thus increasing the loss in the cable.

iii. As the e.m.f induced in the rotor is by mutual induction, if the air gap is increased, the leakage flux will be more and the mutual flux gets reduced, thereby reducing rotor E.m.f, current and torque.

Based on the fore-going, the induction motor should be designed for as small an air gap as mechanically possible, yet large enough to prevent contact between the two (stator and rotor) despite manufacturing tolerances on their dimensions, or movement resulting mechanical deflection and looseness in supporting bearings [4]. The shaft is made short and stiff in order that the rotor may not have any significant deflection as even as small deflection would create large irregularities in the air gap which would lead to production of an imbalance magnetic pull.

Some design guides exist for selecting the air gap dimension necessary to suit any induction motor. The higher the motor speed, the larger the gap length. A common empirical calculation involves rotor peripheral speed, core stack length and rotor diameter. Relations for calculating the length of air gap (l_g) for induction motor include;

i. $l_g = 0.2+2\sqrt{DL}$ mm (1)
ii. $l_g = 0.125+0.35D+0.015\omega_a$ mm (2)
iii. $l_g = 0.2+D$ mm (3)
iv. $l_g = 1.6\sqrt{D} - 0.25$ mm (4)
v. $l_g = \frac{0.007\,D_r}{\sqrt{P}}$ mm (5)
vi. $l_g = \frac{D-D_r}{2}$ mm (6)

Where D = Internal diameter of stator (stator bore) in meter, L = Gross length of stator in meter, D_r = Rotor external diameter in meter, ω_a = Peripheral speed in meter per second, P = Pole pairs. [5]

It is worthy to note that equation 6 is the mathematical definition of length of air gap of most rotating machines.

III. Effect Of Air Gap Length On The Performance Of Synchronous Machines

Just as a great majority of all asynchronous machines are a.c motors (induction motors), so also, a vast majority of all synchronous machines are a.c. generators (alternators). Both synchronous and asynchronous machines can operate reversibly.

An alternator is an a.c. machine which converts mechanical energy into electrical energy, that is, it produces alternating current which changes in value and in direction periodically. The alternators are designed with stationary armature (stator) and rotating field magnet (rotor). The armature which is an iron ring of laminations having slots in its inner sides to hold the conductors is called the stator, while the field system which is revolved between the armature rings is called the rotor. Similar to induction motor, inbetween the stationary armature (stator) and the rotating field magnet (rotor) is a clearance (air gap) whose length greatly influences its performance.

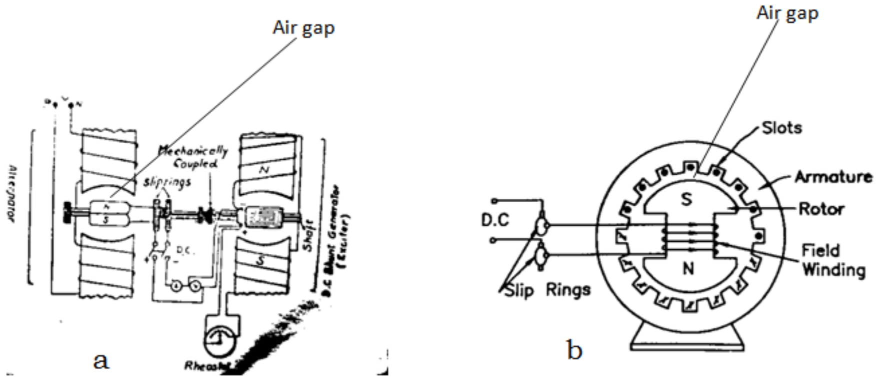


Fig. 2: a-A single phase alternator with exciter [2]
b-A synchronous machine design with a stationary armature and a revolving field structure [5]

The merits and demerits of providing a larger air gap in synchronous machines are;

Merits

i. A large air gap offers a large reluctance to the path of flux produced by the armature mmf and thus reduces the effect of armature reaction.

ii. It brings about higher synchronizing power which makes the machine less sensitive to load variation, better cooling at the gap surfaces, reduction in the noise level and smaller unbalanced pull.

Demerits

With the increase in lengths of air gap;

i. A larger value of field mmf is required
ii. Bigger size of the machine, with a larger diameter of the stator may be involved
iii. There will be increased magnetic leakage
iv. Greater weight of copper in the field winding will be involved
v. There will be increase in the overall cost of the machine

The relations for calculating the length of air gap (l_g) in synchronous machine include;

$$l_g = \frac{AT_g}{0.796 B_g K_g x\, 10^6} \quad (7)$$

$$AT_g = (0.7 \text{ to } 0.75)\, AT_{fo} \quad (8)$$

$$AT_{fo} = SCR \text{ x } AT_a \quad (9)$$

$$AT_a = \frac{1.3 T_{ph} I_{ph} K_w}{P} \quad (10)$$

Where, P = Pair of poles, AT_g= Air gap ampere-turns, AT_{fo}= No load field ampere turns per pole, AT_a= Armature ampere turns per pole, SCR = Short Circuit Ratio, k_w = Stator winding factor, T_{ph} = turns per phase, I_{ph} = Full load current per phase, K_g = Air gap coefficient, B_g = Air gap flux density.

Air gap coefficient (K_g) can be assumed varying from 1.12 to 1.18. SCR for turbo generator may be assumed varying from 0.7 to 1.1, SCR for salient pole alternators may be assumed varying from 0.9 – 1.3 [1]

For salient pole machines of normal construction and having open type slots,

$$l_g = (0.01 \text{ to } 0.15)\, Pp \quad (11)$$

For Turbo- alternators, with massive rotors,

l_g = (0.02 to 0.025) Pp (12)

For synchronous motors designed with maximum output 1.5 times rated output;

l_g = 0.02Pp (13)

where Pp = pole pitch

IV. Effect Of Air Gap Length On The Performance Of Direct Current (D.C) Machines

Direct current machines are the d.c. generators and d.c. motors. They convert mechanical power into electrical power and vice versa of d.c. nature. Their operations are reversible, meaning that the same d.c. machine can work as a generator or as a motor with their satisfactory performance in both the mode of operation.

Direct current machine consists of two major parts Viz, (i) Armature (ii) field system. The arrangement of fundamental parts of a d.c. machine is similar to the one used for synchronous machine, only that the armature winding is placed on the rotor and the field system is housed in the stationary stator. The stationary (field system) and the rotating (Armature) elements of the machine are separated from each other by air gap, which forms the most critical region of the machine for deciding its performance.

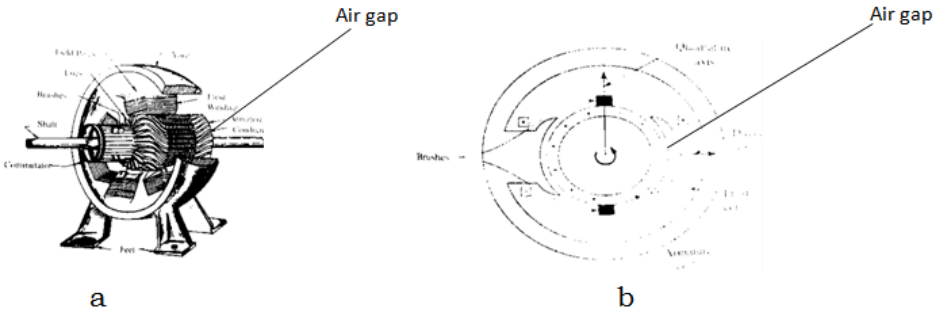


Fig.3: a-A Pictorial representation of D.C machine [3]
b- Schematic representation of a d.c. machine [6]

A commutator, consisting of a large number of commutator segments, properly insulated from each other, with the purpose of converting a.c wave in the armature winding into a d.c. wave at the output terminals in case of d.c. generator, where as in case of d.c. motor, it inverts the d.c. input wave to an a.c. wave in the armature winding [4].

Owing to the influence of air gap length on the machine performance, proper selection of air gap length is governed by the following factors;

i. Cooling: Machines designed with large value of air gap lengths have better ventilation.
ii. Noise: The operation of machines with large air gap length is comparatively quiet.
iii. Armature reaction: The effect of armature reaction is reduced in machines with large air gap lengths.
iv. Bearing and shaft deflection is lesser in machines with large air gap lengths
v. The unbalanced magnetic pull is lesser in machines with large air gap lengths

It can be inferred from the fore-going that larger air gap length is better for smooth D.C machine operation, but will lead to more ampere turns needed to overcome the reluctance of the gap, which directly means more copper in the field winding, increase field copper losses and an overall increase in the cost of the machine. Owing to the above facts, the length of the machine air gap must be so chosen that the main field is sufficiently stiff, so that armature reaction may not distort the field to an undesirable extent. The length of the air gap for d.c. machine can be calculated, based on the values of full load ampere turns per pole (AT_f), field ampere turns per pole (AT_i) and full load armature ampere turns per pole (AT_a) required for the iron parts of the magnetic circuit.

That is, the field ampere turns per pole (AT_{fo}) on no load is given by;

$AT_{fo} = AT_f$ – Field ampere turns per pole (AT_{fc}) to compensate armature reaction on full load. (14)

But the field ampere turns per pole to compensate the armature reaction on load may be assumed from 15% to 20% of the full load armature ampere turns (AT_a)

$\Rightarrow$ AT_{fc} = (0.15 to 0.2) AT_a (15)

$\therefore$Equation 14 becomes;

$\Rightarrow$ AT_{f0} = AT_f - AT_{fc} (16)

The field ampere turns per pole required for the air gap (AT_g) from the field ampere turns per pole on no load (AT_{fo}) and the field ampere turns per pole (AT_i) needed by all the iron parts of the magnetic circuit is given by;

$$AT_g = AT_{fo} - AT_i \qquad (17)$$

But AT_g needed to overcome the machine magnetic resistance (reluctance) is estimated 65% to 70%of $AT_{fo.}$

The effective gap area per pole ($E_{ga)}$ = $K_f P_p L$ (18)

The maximum flux density in the air gap $(B_g) = \frac{\phi}{E_{ga}}$ (19)

For D.C machine, suitable value of air gap coefficient (C_{ag}) varies from 1.15 to 1.18.

The field ampere turns for the gap per meter of gap length $(\frac{AT_g}{l_g})$ is given by;

$$\frac{AT_g}{l_g} = 0.796\, B_g C_{ag} \text{ x } 10^6 \qquad (20)$$

From equation 20,

Length of air gap (l_g) = $\frac{AT_g}{0.796\, B_g C_{ag} \text{ x } 10^6}$ metre

$$= \frac{\left[AT_{f-((0.15\ to\ 0.2)AT_a)-AT_i}\right] - k_f P_p \text{L}}{0.769\, \phi C_{ag} \text{ x } 10^6} \text{ metre} \qquad (21)$$

Where P_p = Machine pole pitch, ϕ = Magnetic flux per pole, L = Armature gross length, K_f = Gap contraction factor (normally assured 1.15).

From the fore-going, it could be observed that in synchronous and d.c. machines, two separate fields interact in the air gap. The a.c. field created by the armature, which is stationary in synchronous machine but rotating in d.c machine, distorts that supplied by the d.c. field, thereby reducing its effectiveness and degrading machine performance. Increasing the air gap reduces the effect of armature reaction. Hence, during designs, these two machines usually have air gap lengths several times larger than those in induction machines.

V. Effect Of Air-Gap Length On The Performance Of Linear Electromechanical Devices (Relays, Electric Door Bell Etc)

Unlike the rotating motions obtainable in rotating machines, translatory (linear) motion is obtainable in most electromechanical devices, such as relays, electric door bells etc. Here the essential parts of the devices include;

i. The fixed part
ii. The movable part (Armature)

Both the fixed part and the movable part form the magnetic core of the system. Inbetween the fixed and the movable part is the air gap with a gap length. The air gap is the non-magnetic part of the magnetic circuit that connects serially and magnetically all other parts in the system to make the flux flow through the gap. The air gap in the system means a magnetic resistance, whose reluctance is proportional to its length and inversely proportional to its cross-sectional area. In relays and other linear electromechanical devices, the air gap is usually an integral part, as it facilitates the movement between the fixed parts (winding and magnetic core) and the active (movable) part (armature), which mechanically drives the main electrical contacts to be connected or disconnected. In the process of electro-mechanical energy conversion in linear system, the air gap plays a vital role, because the stored energy is maximum in the gap.

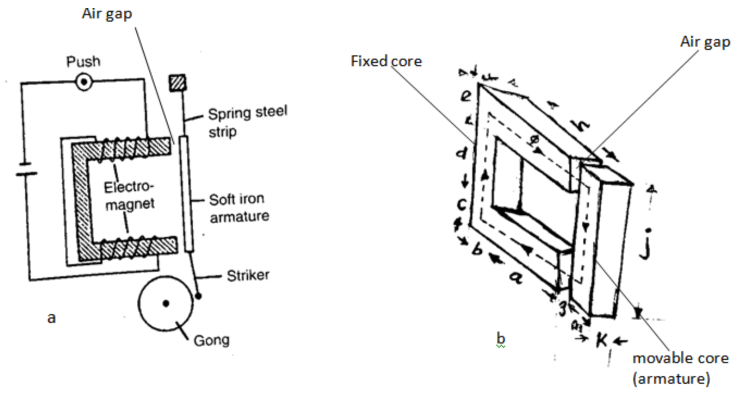


Fig 4: a-The electromechanical door bell [7]
b- The magnetic cores of the electromechanical doorbell with dimensions (in metres)

The influence of the air gap length on the performanceof the device can be illustrated as shown below;
Consider a singly, excited magnetic system shown in fig4a above. It is an electrochemical device with magnetic system of an attracted soft iron armature. Here a coil of N turns wound on the magnetic core forming the electromagnet is connected to an electric source (d.c. source).
Let us suppose that the armature is held stationary at some air gap and the current is increased from zero to some value i. Amperes as a result, magnetic flux (ϕ) will be established in the magnetic system [8]

Total flux linkage $\lambda = N\phi$ (22)

Induced e.m.f, $= \frac{Nd\phi}{dt} = \frac{d}{dt}(N\phi) = \frac{d\lambda}{dt}$ (23)

For the coupling device to absorb energy from the electric circuit, the coupling field must produce a reaction in the circuit. This reaction is the electromotive force e.m.f (e) produced by the magnetic field. The incremental electrical energy (dW_{elect}) due to the flow of current (i) in time dt is;

$dW_{elect} = eidt$ (24)

The energy balance equation in differential form is;

$dW_{elect} = dW_{mech} + dW_{fe}$ (25)

So for the armature is assumed stationary; there is no mechanical output.
Hence, $dW_{mech} = 0$; meaning that all the incremental electrical input energy is stored as incremental field energy (dW_{fe})

$\Rightarrow dW_{elect} = dW_{fe} = eidt$ (26)

Putting equ.23 into equ. 26 we have;

$dW_{fe} = \frac{d\lambda idt}{dt} = id\lambda = Nid\phi$ (27)

$W_{fe} = \int_0^{\lambda} id\lambda = N\int_0^{\phi} id\phi$ (28)

Interestingly, we can still derive another useful expression for the energy stored in the magnetic field as thus;
Assuming l, A, B and H are the length, cross-sectional area, magnetic flux density and magnetic field intensity respectively then;

$Ni = Hl$ and $d\phi = AdB$

$\therefore W_{fe} = N\int_0^{\phi} id\phi = \int_0^{B} HlAdB = Al\int_0^{\boldsymbol{B}} HdB$ (29)

Using the derived equations above, the influence of air gap length (g) on the total mmf and total field energy (W_{fe}) of the magnetic core material of fig4b of the electric door bell, can be investigated as below;
Let the mean length of the flux path be l_c.
If the magnetic intensity of the magnetic core is H_c,

$\therefore$ Mmf in the magnetic core (mmf_c) $= H_c l_c$ (30)

Similarly, magnetic intensity and magnetic flux density in the air gap is H_g and B_g respectively.

$\therefore H_g = \frac{B_g}{\mu_0} = \frac{B_g}{4\pi x 10^{-7}}$ (31)

$\Rightarrow$ Mmf in the air gap (mmf_g) $= H_g$ x 2g Ampere-turns/metre (32)

$\therefore$Total mmf required $= H_c l_c + 2gH_g$ (33)

Where g = air gap length as depicted in fig4b.
Also field energy density in the magnetic core is given by;

$WF_{edc} = \int_0^{B} HdB$ (34)

This energy density is given by the area enclosed between the B-axis and the B-H curve for the magnetic material used.

$\Rightarrow WF_{edc} = ½ \text{ x } B_c \text{ x } H_c$ Joules/metre^3 (35)

Note: $B_g = B_c$ as the same magnetic flux (ϕ) flows through the system.
Volume of the core is given by;

$V_c = ((c+d+e)\, x\, bxk) + (jxmxk) + (axcxk) + (axfx\, e)$ metre^3 (36)

$\therefore$Field energy stored in the core is given by;

$WF_{ec} = WF_{edc} x V_c$ Joules (37)

Similarly, field energy density in the air gap is given by;

$WF_{edg} = \frac{B_g^2}{2\mu_0}$Joules/metre^3 (38)

Similarly, volume of air gap (V_g) = (gxcxk) + (gxexf) metre^3 (39)

NB: f = k, h = (a+b), j = (c+d+e) and all dimensions are in metres.

∴ Field energy stored in the air gap is given by;
$WF_{eg} = WF_{edg} \text{ x } V_g$ Joules (40)

Total stored field energy in the system is given by;
$WF_{ecg} = WF_{ec} + WF_{eg}$ (41)

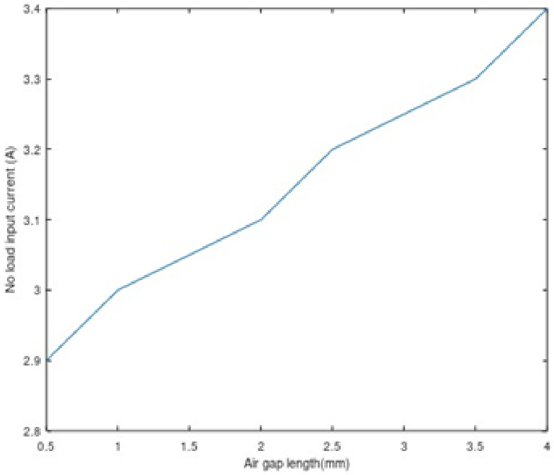
If numerical values are assigned to the dimensions of the magnetic system, one will observe that;
$2gH_g >> H_c l_c$ and $WF_{eg} >> WF_{ec}$
Hence the effect of the air gap on the magnetic core is that most of the field energy is stored in the gap. This is because the reluctance of the air gap is very large as compared to the magnetic core.

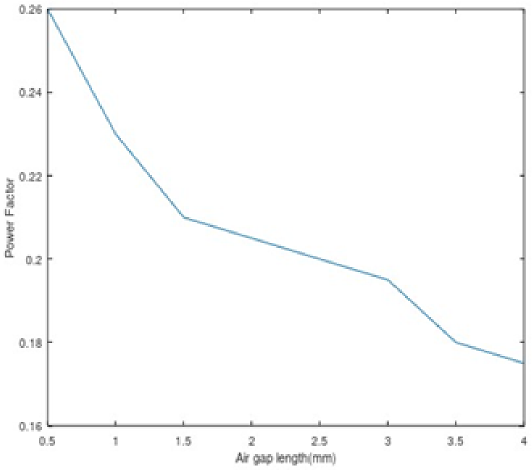
VI. Graphical Implications Of The Effect Of Air Gap Length On Performance Of Rotating Electrical Machnes

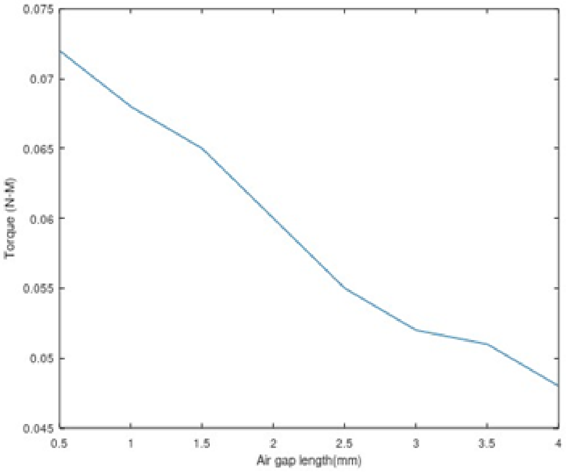
Tabulation for the variation of air gap lengths on no load (input) current, power factor, torque, efficiency, and rotor flux density of rotating electrical machine, necessary for their plots is shown below.

Table 1: An extrapolation from [9]

Air gap Length (l_g) (mm)	**No load input current (io) (A)**	**Power factor (p.f)**	**Torque (N-m)**	**Efficiency (ε) (%)**	**Rotor flux density (B_r) (Tesla)**
0.5	2.9	0.26	0.072	60	0.6
1.0	3.0	0.23	0.068	59	0.52
1.5	3.05	0.21	0.065	57	.0.51
2.0	3.10	0.205	0.06	55	0.48
2.5	3.20	0.20	0.055	51	0.475
3.0	3.25	0.195	0.052	49.5	0.45
3.5	3.30	0.18	0.051	49	0.44
4.0	3.4	0.175	0.048	48.5	0.42







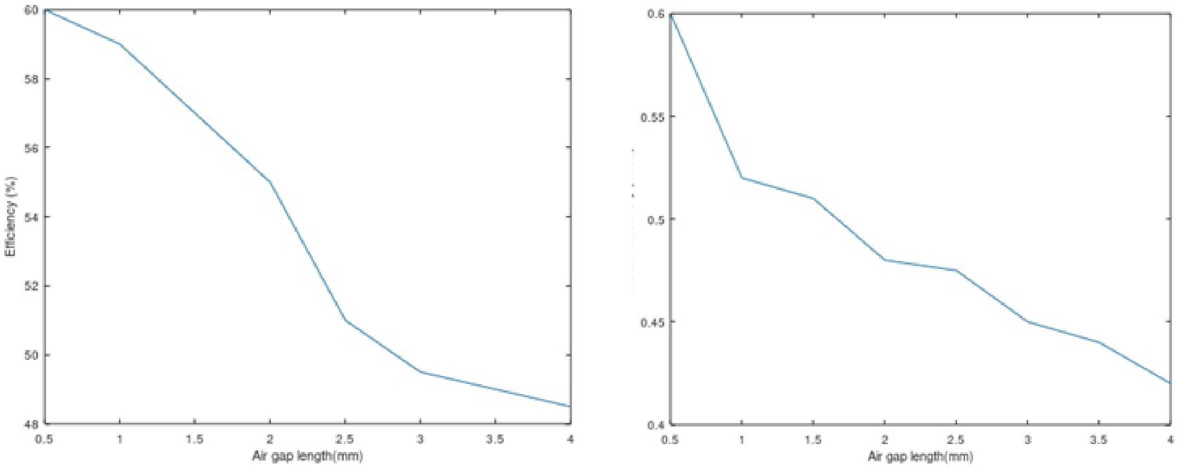


FIG. 5: The graphical representations of the effects of air gap length on the performance parameters of rotating machines

VII. Conclusion

The effect of air gap length on the performance indices of electromechanical devices/machines has been discussed exhaustively.

We have seen how the variations in airgap length affect the machine parameters. Therefore only in machines of high reliability, for mechanical reasons, the air is made larger than the normal size.

References

[1]. V.N Mittle, A Mittal (2008) "Design of Electrical machines" Published by N.C Jain for standard publishers distributors, 1708-B, Nai Sarak, Dehli-110006. Reprint Edition 2008.

[2]. K.B Bhatia (2006) "Practical A.C and D.C motor winding" Published by A.K. Jain for standard publishers distributors 1706-B, Nai Sarak, Delhi-11006. Second Edition

[3]. B.L Theraja, A.K Theraja (2008) "A textbook of electrical technology" Published by S. Chard and Company (AN ISO 9001: 2000 company), Ram Nagar, New Dehli-110055.

[4]. Surva Pattanayak (2015) " M.Tech Power systems and Electrical Engineering, Netaji SUbhash Engineering College"

[5]. A.K Sawhney (2008) "A course in Electrical machine design" Publish by Gagan Kapur for Dhanpat Rai and co. (P) Ltd, 1710, Nai Sarak, Delhi-110006. Sixth Edition.

[6]. Arthur .E. Fitzgerald et al (2003) "Electric Machinery" Published by McGraw-Hill. 1221 Avenue of the Americas, New York, NY 10020. Sixth Edition

[7]. John Bird (2010) "Electrical theory and technology" Published by the Boulevard, Lang Ford Lane, Kidlington, Oxford 0X51GB, UK, 30 corporate Drive, suite 400,Burlington, MA 08103 USA. Forth Edition

[8]. V.K Mehta, Rohit Mehta (2000) "Principles of Electrical Machines" published by S. Chard and Company Ltd. (AN ISO 9001:2000 Company), RAM Nagar, New Dehli-110055.

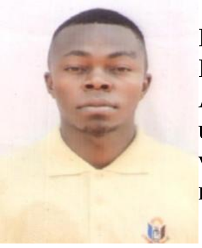
[9]. Mohammed Modarres et al (2010) "Effect of Air Gap variation on characteristics of an Axial flux Hysteresis Motor" A Conference paper-February 2010. First power Electronic and Drive system and technologies conference

AUTHORS PROFILE

Engr. Dr. A.E Anazia is the CEO and Principal partner of A&A Global Engineering Ltd, an M & E Company and member of association for consulting Engineering in Nigeria. He is currently an associate professor, a research fellow in power system and machines in Faculty of Engineering, Nnamdi Azikiwe University Awka, Anambra State Nigeria.

Obute Kingsley Chibueze is a seasoned lecturer of the department of Electrical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria. He majors in Electrical machines (with specific interest on Electric motors) up to Ph.D level. He has published many Journals and Texts to his credit. He is a registered Electrical Engineer with Coren.

Prof. Olufolahan Oduyemi is currently an Associate Professor of Facilities and Construction Project Management at the Southeast Missouri State University, Cape Girardeau, Missouri, USA. He had his Bachelors degree in Estate Management from the Federal University of Technology, Akure, Ondo State Nigeria in 2008, his Masters degree in Property Management and Investment from Edinburgh Napier University, Scotland, UK in 2011, a PhD in Facilities Management from University of Derby, UK in 2015 and a Masters in Business Administration (MBA) from Southeast Missouri State University, Cape Girardeau, Missouri, USA in 2019.



Eze Chikwado Emmanuel is a graduate assistant and a masters student in the department of Electronic and Computer Engineering, Faculty of Engineering in Nnamdi Azikiwe University, Awka, Anambra state, Nigeria. I interned with Electronic development institute where I undertook research in the application of computational intelligence such as fuzzy logic in various engineering disciplines. Currently working on application of deep convolutional neural networks in medical image diagnosis

Obute Kingsley Chibueze, et. al. “Imperatives of Air-Gap Length on the Performance of Electromechanical Devices/Machines.” *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 15(3), (2020): pp. 15-23.