CALCULATION IN THE FIELD OF SEGMENTAL ROTOR MACHINES TAKING INTO ACCOUNT WINDING HARMONICS AND ROTOR AIRGAP IRREGULARITIES

BY

*L. A. AGU

ABSTRACT

The stator mmf over a segment of the segmental rotor reluctance machine is treated as an infinite array of generators feeding a common busbar, and the magnetic potential of the rotor segment is obtained as the potential of the equivalent busbar. The rotor potential for any airgap profile is readily obtained and it is shown how the method may be extended to axially laminated machines and those of the flux barrier type. This approach is derived from considering the flux due to a single stator conductor carrying current.

1. INTRODUCTION

A feature of the analysis of segmental rotor reluctance machines is the necessity to determine the magnetic potential as zero, because the rotor, unlike that of the segmental machine is one integral piece. The magnetic potential manifests itself in the reversal of flux in the air gap. In reference [1] the quadrature axis potential was evaluated by using the fact that flux cannot accumulate on the pole, and noting that at the point of reversal, the rotor potential must equal the stator applied magnetic potential. The method was further extended in reference [2] to include a rotor with channels cut over the central part of each segment.

The rotor potential is calculated in this paper by considering the stator mmf as an infinite array of parallel generators feeding a common busbar (the rotor segment) and the internal impedance of each generator represents the reluctance of the airgap at the point of action of each of these generators. The parallel generator approach adopted here leads to the same basic expression for rotor potential as in ref. [1] and [3]. The determination of the rotor potential is however extended to include any rotor air gap configuration and shows how harmonicas of stator mmf are taken into account.

2. FLUX DUE TO A SINGLE STATOR CONDUCTOR

In fig. 1(a) is shown a rolled-out segmental-rotor machine, and also shown are flux paths of a single stator conductor which lies over one of the rotor segments. Most of the flux will follow the path AA shown in the diagram. No serious error will result if all the flux is regarded as confined to that path. This means that all fringing flux using paths like BB and flux between adjacent segment, i.e. using paths such as CC and DD are ignored. The flux density distribution due to current in the single stator conductor will have the form show in fig. 1(b). If R_X and R_Y represent the magnetic reluctances of the airgap between the section of segment of width X and the complementary section of width Y respectively, then the amplitude B_1 and B_2 of the rectangular wave of flux density distribution are given by

$$B_1 = \frac{\mathrm{i}}{(\mathrm{R_X}+\mathrm{R_Y})\mathrm{x}} = \frac{\mathrm{iy}}{\mathrm{g}\beta}$$

$$B_2 = \frac{i}{(R_X + B_Y)y} = \frac{ix}{g\beta}$$

3. FLUX DUE TO A SYMMETRICALLY WOUND STATOR WITH FULL PITCH COILS

Consider the same segmental rotor machine which has a single stator slot per pole in a symmetrical arrangement. Let each slot machine contain a conductor carrying current *i* amps with directions as indicated in Fig. 2(a). The flux density distribution over two pole pitches will be as shown in Fig. 2(b). The values of B_1 and B_2 are the same as obtained for Fig.1(b).

If the airgap flux density was calculated using the product of mmf distribution. Fig. 3(c) and the permeance distribution Fig. 3(d) of the air gap *b* between rotor segment and stator, the result will be as shown in Fig. 3(a). The height of the graph of Fig. 3(a) is 1/2g. This graph clearly differs from that of Fig. 2(b). In fact the algebraic difference between the two graphs is the graph of Fig. 4. The height of the graph of Fig. 4 is $\frac{i}{2g}\frac{y-x}{\beta}$

It represents a flux density distribution acting in opposition to the flux density distribution of Fig. 3(a). It is as if the rotor segments acquire potentials and become sources of mmf directing flux into the stator.

*Mr. L. A. Agu is a Reader in Department of Electrical and Electronic Engineering of the University of Nigeria, Nsukka

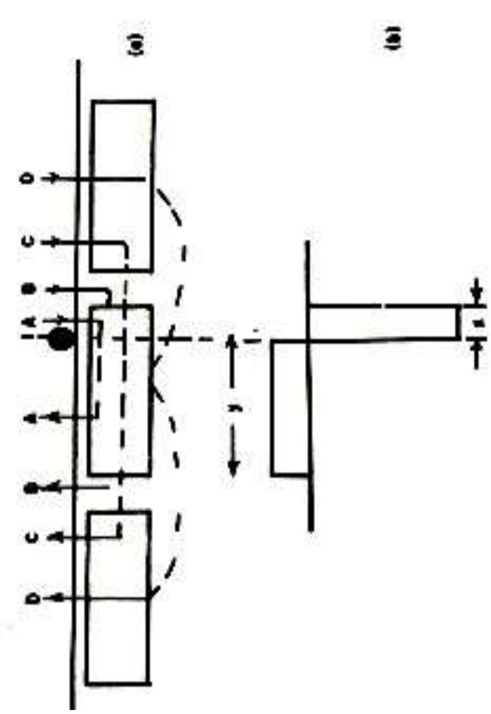

Fig.1. Flux density distribution of a single stator conductor

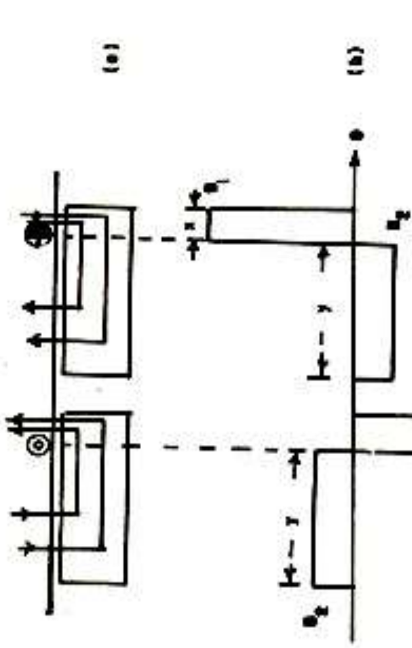

Fig.2. Flux density distribution of a single coil.

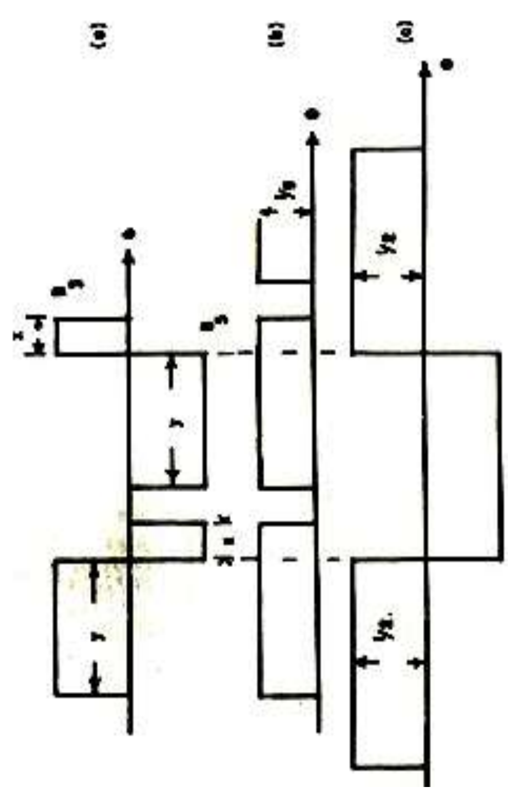

Fig.3. Flux density distribution due to rotor potential

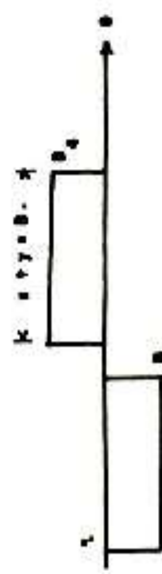

Fig.4. Algebraic difference between figures 3(a) and 2(b).

Therefore, if the mmf method used in normal machine analysis is to apply to segmental rotor machines, the effect of this rotor potential must be taken into account.

The net flux density will be the difference between what it would have been if the rotor potential were zero minus the flux density produced by the difference between the potential of the rotor and that of the stator (assumed zero).

4. CALCULATION OF ROTOR SEGMENT POTENTIAL

The polarity of the rotor potential alternates between adjacent segments. It follows that the zero potential will coincide with the dotted lines as shown in Fig.5. Let the effective reluctance of the flux paths between segment and the zero potential be R_o, the Parallel- Generator Theorem can be used to determine the rotor potential. The mmf acting at the airgap over the rotor in Fig. 5 is $\frac{i}{2}$, this acts downwards over the section x of reluctance R_X and downwards over the section y of reluctance R_y. The potential M of the rotor is given by the equation:

$$\left(\frac{I}{2}-M\right)\frac{1}{R_X}+\left(\frac{I}{2}-M\right)\frac{1}{R_y}=\frac{M}{R_o}$$

Or $$\frac{I}{2}\left(\frac{1}{R_X}-\frac{1}{R_y}\right)=M\left(\frac{1}{R_X}+\frac{1}{R_y}+\frac{1}{R_o}\right)$$

The expression is $\frac{I}{2}\left(\frac{1}{R_X}-\frac{1}{R_y}\right)$ equivalent to $\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F_1(\theta-\alpha)\quad(\theta)\quad d\theta$

Where $F_1(\theta-\alpha)$ is the mmf distribution and (θ) the permeance distribution expressed as Fourier series.

The expression $\left(\frac{1}{R_X}+\frac{1}{R_Y}\right)$, the total permeance of the airgap over the segment is also given by

$$\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}}(\theta)d\theta \quad = \quad T$$

$$\therefore \quad M=\frac{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F_1(\theta-\alpha_1)\quad(\theta)\quad d\theta}{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}}(\theta)\quad d\theta+\frac{1}{R_O}}$$

$$=\frac{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F_1(\theta-\alpha_1)\quad(\theta)\quad d\theta}{T+\frac{1}{R_O}}$$

4.1. FLUX DENSITY OF A NUMBER OF COILS

The flux density distribution due to any other group of symmetrical conductors can be similarly obtained. Provided there is no saturation in the magnetic circuit, the total flux density distribution will be the sum of the separate flux density distributions. The flux density distribution of a representative coil can be expressed as

$$\left[F_n(\theta-\alpha_n)x-M_n f(\theta)\right](\theta)$$

Where $F_n(\theta-\alpha_n)x$ in the mmf distribution of the coil, M is the rotor potential due to that coil and $f(\theta)$ is a function in Fourier Series, that takes into account the area occupied by the rotor segments and also their polarity.

The flux density distribution due to all coils of the stator will be

$$\sum_n F_n(\theta-\alpha_n)x(\theta)-(\theta)f(\theta)\sum_n M_n$$
$$=F(\theta-\alpha)x(\theta)-(\theta)f(\theta)\sum_n M_n$$

Where $F(\theta-\alpha)$ in the resultant mmf due to all coils expressed as a Fourier series

$$\sum M_n=\frac{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F_n(\theta-\alpha_n)\quad(\theta)\quad d\theta}{T+\frac{1}{R_O}}$$

Which is the same as

$$\frac{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F(\theta-\alpha)\quad(\theta)\quad d\theta}{T+\frac{1}{R_O}}$$

Where T is the total permeance

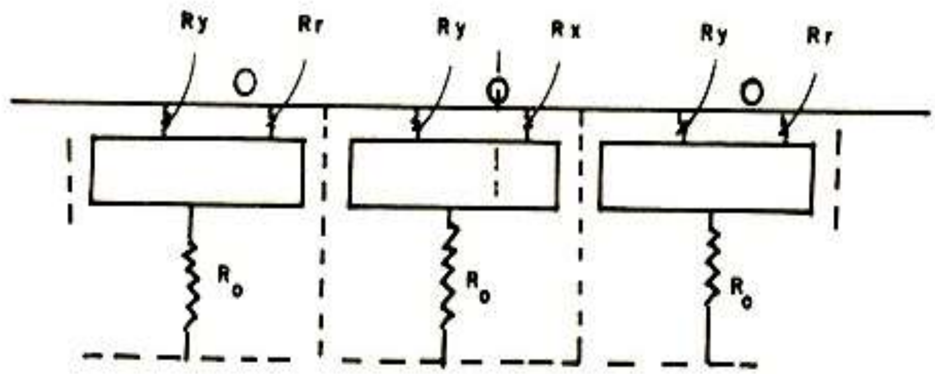

Fig.5. Network equivalent of the airgap permeances.

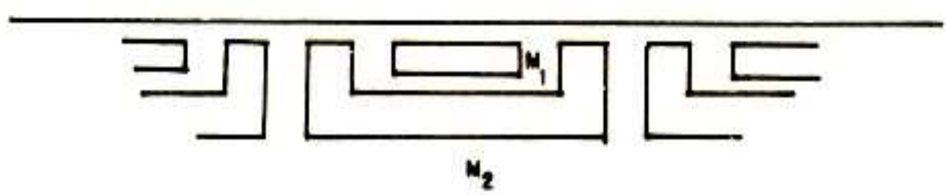

Fig.6. Basix two sleeve machine.

$$\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} (\theta) \quad d\theta$$

The total flux density distribution may therefore be written

$$\left(\left[F(\theta-\alpha)-f(\theta)\frac{\int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F(\theta-\alpha) \quad (\theta) \quad d\theta}{T+\frac{1}{R_O}}\right](\theta)\right)$$

5. ROTOR WITH CENTRAL CHANNEL

Using the methods outlined above, the rotor potential and the flux density distribution were calculated for a rotor with a central channel. The results are exactly as given in ref. [2].

6. INTERLEAVED ROTOR MACHINE

This method can be applied very readily to the analysis of an interleaved segmental [3] rotor machine (Fig. 6). Let M_A and M_B be the potentials of the outer and inner rotor sleeves respectively. These can be computed from the following expressions

$$M_A - M_B = \int_{-\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} \frac{F(\theta-\alpha)\beta_A(\theta)d\theta}{T_A+\frac{1}{R_{AB}}} + M_B(T_B+\frac{1}{R_B}) - (M_A-M_B)/R_{AB}$$

$$= \int_{\frac{-\beta\pi}{2}}^{\frac{-\beta\pi}{2}} F(\theta-\alpha)\beta(\theta)d\theta + \int_{\frac{\beta\pi}{2}}^{\frac{\beta\pi}{2}} F(\theta-\alpha)\beta(\theta)d\theta$$

The flux density in the stator airgap will be given by

$$\lfloor F(\theta-\alpha)-f_A(\theta)(M_A-M_{B)]}\rfloor\beta_A(\theta)$$
$$+[F(\theta-\alpha)-M_B f_B(\theta)]\beta_B(\theta)$$

where $\beta_A(\theta)$ and $f_A(\theta)$ are respectively the permeance and potential functions when the inner sphere is removed, SB(θ) and f (θ) are respectively the performance and potential functions when the outer sphere is removed, $\beta_B(\theta)$ and $f_B(\theta)$ are respectively the permeance and potential functions when the outer sleeve is removed and the centre channel that is left is regarded as having infinite reluctance, T_A is the total reluctance of the airgap between the outer sleeve and the stator and T_B is the total reluctance of the airgap between the inner sleeve and the stator. The calculation of the flux density distribution in a machine with an axially laminated rotor will follow much the same line of reasoning, only that more sleeves are to be considered [4]. The flux-barrier machine is only a special case of the multilevel rotor machine [5].

7. CONCLUSION

The method described above yields the same result for rotor potential and is equivalent to the other method in which the rotor potential is calculated by determining the point of flux reversal. However it has the important advantage that the single expression that results, gives the flux density distribution as a function of the position of the rotor relative to the stator mmf axis. This is important when considering the field of reluctance frequency changers where it is desirable that the output emf be known as a continuous function of the rotor displacement. Effects of stator harmonics and their relationship with harmonics of rotor permeance distribution for production of synchronous torque at different field synchronous speeds are easily established. This is useful for dealing with multispeed [6] and charge pole [7] machines.

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