A NEW APPROACH TO ELECTROMAGNETIC RECTIFICATION AND INVERSION

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A NEW APPROACH TO ELECTROMAGNETIC

RECTIFICATION AND INVERSION

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PREFACE

The main reason for the low efficiency of conventional rotary converters is the power loss due to windage and friction. If the relative motion between the armature and the stator can be avoided by some means or other, the efficiency might be comparable to that of a transformer. This can be achieved by making use of the constant rotating magnetic field of a polyphase winding and a synchronously-driven brush system, the units of which pass over fixed commutator segments. It is conceivable that in this way rectification of alternating current supplied to polyphase winding is possible. The machine based on this principle is called the "transverter". It operates also as an inverter.

The first part of this investigation consists of a mathematical analysis of voltage transformation in the transverter. The latter portion is devoted to the experimental verification. The experimental and analytical results are in agreement. The torque and power transformation are not included in this thesis. These could well be subjects for further investigation.

I wish to express my sincere appreciation to my adviser, Professor Claude M. Summers for his guidance and encouragement. Indebtedness is also acknowledged to the School of Electrical Engineering for the use of its laboratory facilities.

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CHAPTER I

INTRODUCTION

Motor-generator sets have been the normal source of power for large d.c. motors for many years. But since the last ten to fifteen years, a tremendous increase in the use of rectifiers is being observed. There are two main reasons for the downfall of the electromagnetic machines in the field of rectification: (1) comparatively high initial and maintenance cost and (2) low efficiency. Both of these drawbacks, to a considerable extent, are due to the presence of a huge rotor in such machines. If by some means or other, we can avoid the relative physical motion between the stator and the rotor, or the field and the armature, appreciable reduction in the cost and increase in the efficiency can be expected.

In the usual d.c. machine, voltage is induced in the armature when it is rotated in a constant magnetic field by a prime mover while the brushes are held stationary on the commutator. Exactly the same results will be obtained if the armature is kept stationary and the brushes and the constant magnetic field are rotated at the same speed and in the same direction, with respect to the rotor. From the theory of polyphase machines, we know that when a sinusoidally alternating voltage is applied to a polyphase winding, a constant rotating magnetic field is produced. If we make use of such a rotating field together with a synchronous brush drive, then we have a machine at our disposal which represents all the features of a d.c. generator, yet there is no rotation of armature itself with respect to the field. A.C. power supplied to the polyphase winding will be transformed to the d.c. armature via the rotating magnetic field. D.C. voltage will be available across the brushes.

The purpose of this report is to analyze the voltage transformation from a.c. to d.c. or vice versa in a machine which operates under an arrangement as indicated above and to experimentally verify the results. Torque and power transformation are not included in this study.

For analysis, two separate setups are considered:

(a) Single phase a.c. winding with conventional armature winding on d.c. side.

(b) Two-phase a.c. winding with conventional armature winding on d.c. side.

The discussion can be extended to polyphase machines easily. The equations derived are for d.c. to a.c. conversion. But the same equations with little or no change may be used for a.c. to d.c. conversion. The equations are qualitatively verified on Westinghouse Electric Corporation Generalized Machine in the School of Electrical Engineering Laboratory. Oscillographic pictures of the results are also included.

CHAPTER II

DESCRIPTION OF THE PROPOSED MACHINE

A physical conception of the proposed machine is necessary before its mathematical analysis is presented. This Chapter will give a brief description of such a machine, which will be referred to as a transverter[1] in the following pages.

The essential features of the transverter are shown schematically in Figure 1.

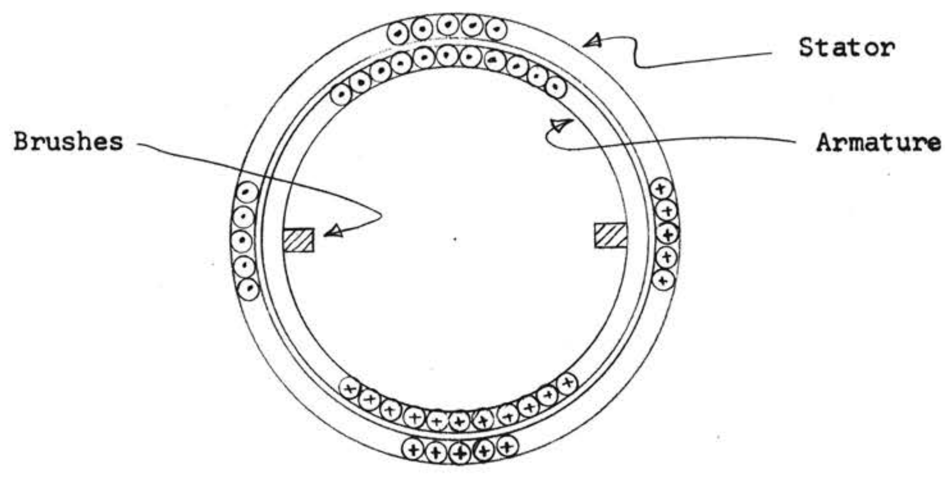

Figure 1. Transverter Schematic Diagram

The inner winding is a conventional d.c. armature winding, and the

[1]H. Cotton, Electrical Technology (Sir Isacc Pitman Press, 1950), p. 425.

outer winding is similar to that of a two-phase alternator stator winding. Even though in operation both the windings will be stationary, the outer winding will be referred to as "stator winding". The brushes are the only moving parts of the machine. Unlike in a conventional d.c. machine, here the brushes will be sliding over the stationary commutator (not shown in the schematic diagram) which is a part of the armature unit. The brush drive is also not shown in Figure 1. The brush drive is an auxiliary part of the transverter. The external load on the brush drive is only due to friction between the brushes and the commutator, so the load on the brush drive motor is independent of the load on the transverter itself. Thus in general, a fractional h.p. motor will do the job of the brush drive. As it is explained later, this auxiliary motor must run at synchronous speed for a.c. to d.c. conversion. In d.c. to a.c. conversion, the speed of the brush drive determines the frequency of the a.c. output voltage. Since in this case d.c. power would be available, a shunt motor would best suit the purpose.

When the transverter is used to convert a.c. to d.c., we have to have a multiple- or split-phase stator winding. Such a winding when connected to an a.c. source produces a constant magnetic field which rotates at synchronous speed corresponding to the supply frequency. Now if the brushes are driven in synchronism with the rotating magnetic field and in the same direction, then we can say that the armature is rotating (in the opposite direction) with respect to the field exactly like the armature of a conventional d.c. generator. Hence, d.c. output is obtained across the brushes. It must be noted that multiple- or split-phase stator winding and synchronous brush drive are essential for a.c. to d.c. conversion.

Next, the reverse operation of the transverter will be considered. If a d.c. source is connected across the stationary brushes, the current will be determined by the armature and brush contact resistances. The armature current will produce constant and stationary magnetic field directed along the brush-axis. If the brush-carriage is given a tilt, the magnetic field will also experience a tilt; that is, the magnetic field axis will follow the brush axis. Now if the brushes are rotated at certain speeds with the d.c. source still connected across the brushes, the constant magnetic field will rotate along with the brushes at the same speed and in the same direction. What does this rotation of constant magnetic field mean to the stator winding? The armature together with the brushes is now behaving like the rotating cylindrical pole rotor of an alternator. Hence a.c. output will be obtained across the stator terminals. The frequency of the a.c. voltage generated depends on the speed of the brush drive. For a.c. to d.c. conversion, there are no apparent restrictions on the number of phases of the stator winding. In the next Chapter it will be shown that single-phase stator winding is not very desirable. Also, it will be shown that when the brushes are rotating, the armature current depends not only on its resistance but also on its inductance.

In the above discussion it is understood that there are two brushes and that the armature and the stator are wound for two poles. But the arguments hold true for any number of brushes and poles, so long as the choice of number of brushes and number of poles is consistent.

CHAPTER III

MATHEMATICAL ANALYSIS

The purpose here is not to derive accurate design formulas but to give a feeling for how the voltage transformation takes place from d.c. to a.c. or vice versa. It would be a repetition of the same work if the equations are derived for a.c. to d.c. and d.c. to a.c. transformation separately. For the following two reasons, equations are derived for d.c. to a.c. transformation:

(i) D.C. to a.c. transformations are not limited to multiple-phase stator windings; therefore, transverters with single-phase stator winding may also be considered.

(ii) The Westinghouse Electric Corporation Generalized Machine used for experimental verification of the results obtained from the mathematical analysis incorporates a d.c. motor as the brush drive. Naturally, it is not possible to run the brushes at synchronous speed. Hence, voltage transformation from a.c. to d.c. is not possible with this machine.

In the analysis, first a transverter with single-phase winding will be considered and then one with two-phase stator winding. The choice of two-phase winding for a multiple-phase case is also not arbitrary. The stator of the Generalized Machine is wound for two phases.

Single-Phase Transverter

The following nomenclature is used in the analysis:

I_a - Constant (d.c.) armature current.

i_a - Instantaneous current in the armature conductors not undergoing commutation, i.e., current in non-commutating armature conductors.

i_c - Instantaneous current in the armature conductors undergoing commutation, i.e., current in commutating armature conductors.

i_s - Instantaneous (a.c.) current in the stator winding.

I_s - Maximum value of the stator current.

L_{aa} - Self-inductance of the entire armature winding.

L'_{aa} - Self-inductance of the non-commutating armature conductors.

L_{cc} - Self-inductance of the commutating armature conductors.

L_{ss} - Self-inductance of the stator winding.

ℓ_{as} - Mutual-inductance between entire armature winding and the stator winding as a function of the position of the brushes.

L_{as} - Maximum value of ℓ_{as}.

ℓ'_{as} - Mutual-inductance between non-commutating armature conductors and the stator winding as a function of the position of the brushes.

L'_{as} - Maximum value of ℓ'_{as}.

ℓ_{cs} - Mutual-inductance between commutating armature conductors and the stator winding as a function of the position of the brushes.

L_{cs} - Maximum value of ℓ_{cs}.

r_a - Total armature resistance.

r'_a - Resistance of non-commutating armature conductors.

r_c - Resistance of commutating armature conductors.

r_s - Stator winding resistance.

v_a - Armature induced voltage.

v_{at} - Armature terminal voltage.

v_s - Stator induced voltage.

v_{st} - Stator terminal voltage.

α - Brush width in radians.

θ - Angular displacement in radians.

ω - Angular velocity of the brush drive in radians/second.

ω - Angular frequency of the alternating current output.

In the analysis below it is assumed that the armature winding and the stator winding are uniformly distributed. Linear commutation is also assumed.

Consider the armature winding alone when connected across a d.c. source as in Figure 2.

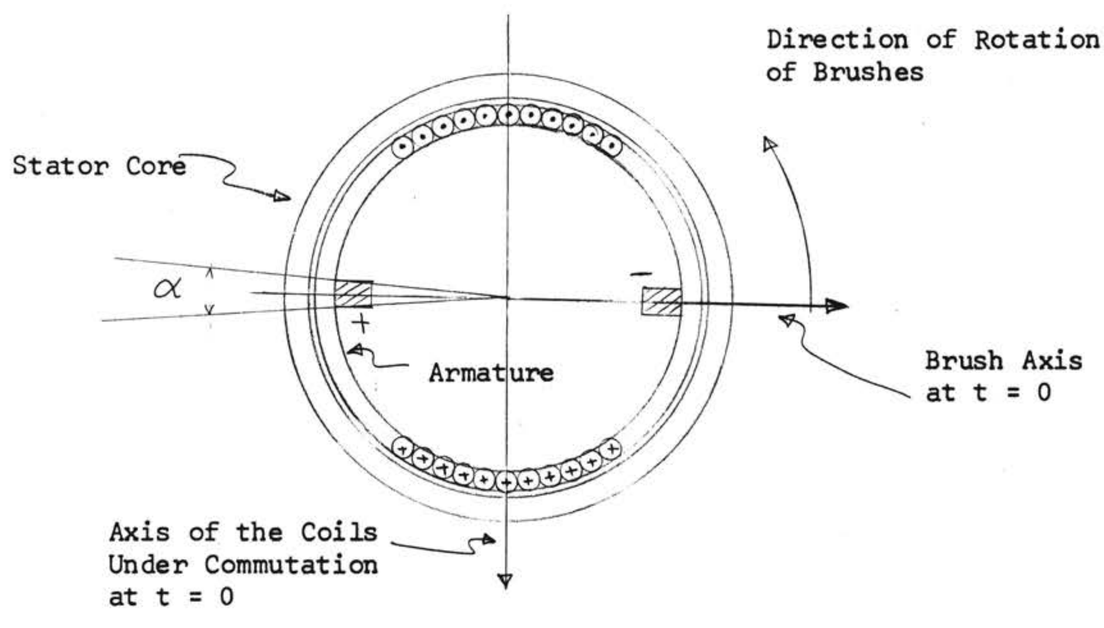

Figure 2. Stator Core and Armature with Brushes

$$v_{ta} = (i_a\, r_a' + i_c\, r_c) + \frac{d}{dt}(i_a\, L_{aa}' + i_c\, L_{cc}) \tag{1}$$

In Equation 1, $(i_a\, r_a' + i_c\, r_c)$ can be replaced by the total armature resistance voltage drop $I_a\, r_a$; i_a is the same as I_a; L_{aa}' and L_{cc} are time invarient. The mutual inductance between the commutating and the non-commutating coils of the armature is not considered as the axes of these two coils are mutually orthogonal for any position of the brushes. Since the self-inductance of a coil is a function of its physical dimentions and the number of turns; and since uniform distribution of armature conductors is assumed, it follows that:

$$L_{cc} = \frac{\alpha}{\pi} L_{aa} \tag{2}$$

$$L_{aa}' = \frac{\pi - \alpha}{\pi}\; L_{aa} \tag{3}$$

Thus, Equation 1 reduces to

$$v_{ta} = I_a\, r_a + \frac{\alpha}{\pi} L_{aa} \frac{di_c}{dt} \tag{4}$$

Figure 3 illustrates the waveform of current in an armature coil with linear commutation; t_c is the commutation time.

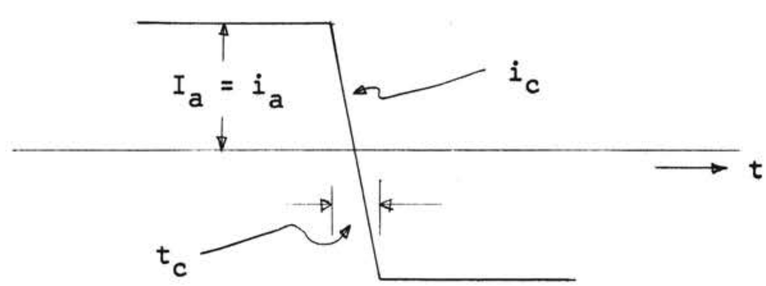

Figure 3. Waveform of Current in an Armature Coil with Linear Commutation

If ω is the angular velocity of the brushes,

$$t_c = \frac{\alpha}{\omega} \text{ Seconds} \tag{5}$$

Therefore,

$$\frac{di_c}{dt} = \frac{I_a}{\alpha/\omega} = \frac{I_a\ \omega}{\alpha} \tag{6}$$

From Equation 4 and 6:

$$v_{ta} = I_a\ r_a + \frac{\alpha}{\pi} L_{aa} \frac{I_a\ \omega}{\alpha}$$

That is,

$$v_{ta} = I_a\ (r_a + \frac{\omega\ L_{aa}}{\pi}) \tag{7}$$

Next, consider the stator winding alone as in Figure 4.

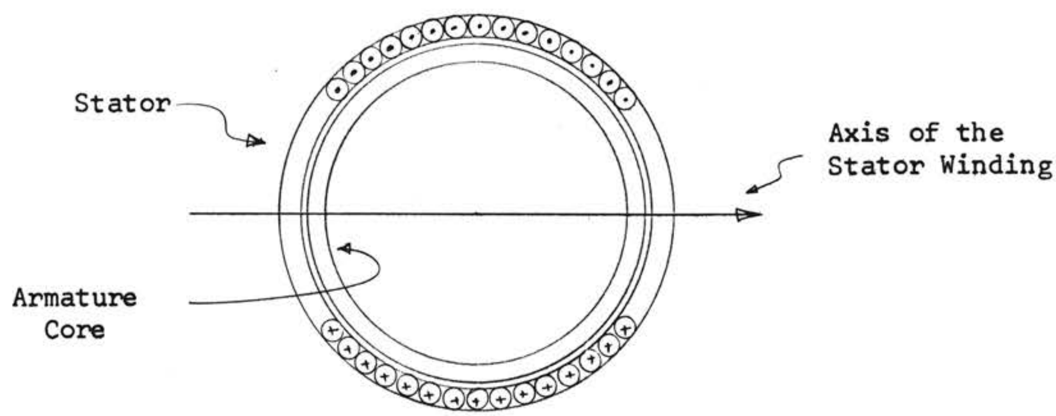

Figure 4. Stator Winding and Armature Core

If the stator is connected to an a.c. source,

$$v_{ts} = i_s\ r_s + \frac{d}{dt}\ (L_{ss}\ i_s) \tag{8}$$

With L_{ss} being constant, Equation 8 reduces to

$$v_{ts} = i_s r_s + L_{ss} \frac{di_s}{dt} \tag{9}$$

Finally, we consider the complete single-phase transverter. Figure 5 shows such a machine schematically.

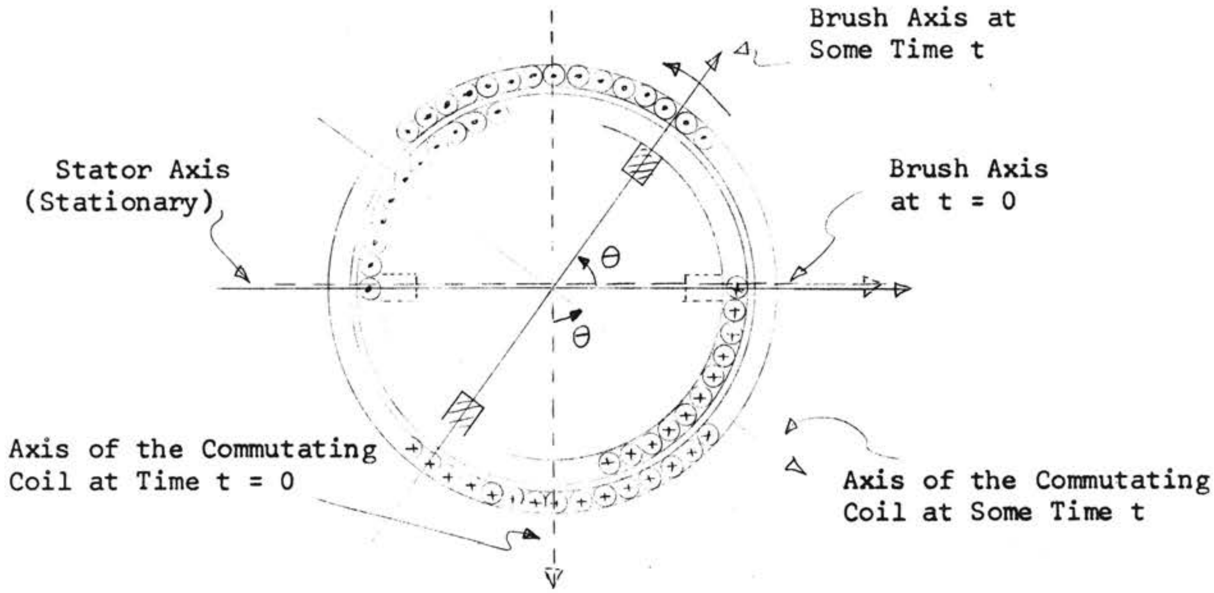

Figure 5. Schematic Diagram of Single-Phase Transverter

If the stator is open circuited and the armature is connected across a d.c. source, Equation 4 still holds true, and the voltage induced in the stator winding is given by

$$v_s = \frac{d}{dt} (\ell'_{as} i_a + \ell_{cs} i_c)$$

i.e.,

$$v_s = I_a \frac{d}{dt} (\ell'_{as}) + \ell_{cs} \frac{di_c}{dt} + i_c \frac{d\ell_{cs}}{dt} \tag{10}$$

From Figure 5 it can be seen that

$$\ell'_{as} = L'_{as} \cos \theta$$

$$= L'_{as} \cos \omega t \qquad (11)$$

$$\ell_{cs} = L_{cs} \cos (\omega t - \pi/2)$$

$$= L_{cs} \sin \omega t \qquad (12)$$

Also, since the reluctance of the magnetic path is independent of the position of the brushes, and since the windings are assumed to be uniformly distributed, the following equations are justified:

$$L_{cs} = \frac{\alpha}{\pi} L_{as} \qquad (13)$$

$$L'_{as} = \frac{\pi - \alpha}{\pi} L_{as} \qquad (14)$$

From Equations 10, 11, 12, 13, and 14:

$$v_s = I_a \frac{d}{dt} (\frac{\pi - \alpha}{\pi} L_{as} \cos \omega t) + \frac{\alpha}{\pi} L_{as} \sin \omega t \frac{di_c}{dt} +$$

$$i_c \frac{d}{dt} (\frac{\alpha}{\pi} L_{as} \sin \omega t) \qquad (15)$$

After performing differentiation in Equation 15,

$$v_s = -I_a \frac{\pi - \alpha}{\pi} L_{as} \omega \sin \omega t + \frac{\alpha}{\pi} L_{as} \sin \omega t \frac{I_a \omega}{\alpha} +$$

$$i_c \frac{\alpha}{\pi} L_{as} \omega \cos \omega t. \qquad (16)$$

$$= -L_{as} \omega I_a (1 - \frac{1 + \alpha}{\pi}) \sin \omega t + \frac{\alpha}{\pi} L_{as} \omega i_c \cos \omega t \qquad (17)$$

In an actual machine $\frac{\alpha}{\pi}$ is very small; for the Generalized Machine it is about 1/18. For approximate results, this quantity might be considered negligible. This is also desirable in order to get rid of i_c in Equation 17, which is rather difficult to handle within the scope of this thesis. Disregarding $\frac{\alpha}{\pi}$, Equation 17 reduces to

$$v_s = - L_{as}\ \omega\ I_a \left(\frac{\pi - 1}{\pi}\right) \sin \omega t \tag{18}$$

Next consider the case when a load is connected across the stator terminals. Assume

$$i_s = -I_s \sin \omega t \tag{19}$$

It might be noted that the output current is assumed to be in phase with the output voltage. This assumption is made for simplicity. While discussing two-phase transverters, a more general case is considered.

The stator winding has some internal resistance and self-inductance associated with it. Considering the impedence drop in the winding, stator terminal voltage equation may be written as:

$$v_{ts} = v_s - [r_s\ i_s + \frac{d}{dt} (L_{ss}\ i_s)]$$

$$= v_s - [-r_s\ I_s \sin \omega t - L_{ss}\ I_s\ \omega \cos \omega t] \tag{20}$$

Therefore from Equations 18 and 20:

$$v_{ts} = -L_{as}\ \omega\ I_a \left(\frac{\pi - 1}{\pi}\right) \sin \omega t + I_s\ (r_s \sin \omega t + \omega\ L_{ss} \cos \omega t) \tag{21}$$

In the presence of stator current, Equation 7 for v_{ta} needs to be modified to account for additional flux linkages. With this modification

$$v_{ta} = I_a \left(r_a + \frac{\omega L_{aa}}{\pi}\right) + \frac{d}{dt}(\ell'_{as}\, i_s) + \frac{d}{dt}(\ell_{cs}\, i_s) \qquad (22)$$

From Equations 11 and 19:

$$\frac{d}{dt}(\ell'_{as}\, i_s) = -I_s \sin \omega t \frac{d}{dt}(L'_{as} \cos \omega t) + L'_{as} \cos \omega t \frac{d}{dt}(-I_s \sin \omega t)$$

$$\frac{d}{dt}(\ell'_{as}\, i_s) = + I_s L'_{as}\, \omega \sin^2 \omega t - I_s L'_{as}\, \omega \cos^2 \omega t$$

$$\frac{d}{dt}(\ell'_{as}\, i_s) = -I_s\, \omega L'_{as} (\cos^2 \omega t - \sin^2 \omega t)$$

$$\frac{d}{dt}(\ell'_{as}\, i_s) = -I_s\, \omega L'_{as} \cos 2\omega t \qquad (24)$$

From Equations 14 and 24:

$$\frac{d}{dt}(\ell'_{as}\, i_s) = -\frac{\pi - \alpha}{\pi}\, \omega L_{as} I_s \cos 2\omega t \qquad (25)$$

From Equations 12 and 19:

$$\frac{d}{dt}(\ell_{cs}\, i_s) = -I_s \sin \omega t \frac{d}{dt}(L_{cs} \sin \omega t) + L_{cs} \sin \omega t \frac{d}{dt}(-I_s \sin \omega t)$$

$$\frac{d}{dt}(\ell_{cs}\, i_s) = -I_s L_{cs}\, \omega \sin \omega t \cos \omega t - I_s L_{cs}\, \omega \sin \omega t \cos \omega t$$

$$\frac{d}{dt}(\ell_{cs}\, i_s) = -2\, I_s\, \omega L_{cs} \sin \omega t \cos \omega t$$

$$\frac{d}{dt}(\ell_{cs}\, i_s) = -I_s\, \omega L_{cs} \sin 2\omega t \qquad (26)$$

From Equations 13 and 25:

$$\frac{d}{dt}(\ell_{cs}\ i_s) = -\frac{\alpha}{\pi} I_s\ \omega\ L_{as}\ \sin 2\omega t \tag{27}$$

From Equations 22, 25, and 27:

$$v_{ta} = I_a\ (r_a + \frac{\omega\ L_{aa}}{\pi}) - (\frac{\pi - \alpha}{\pi} \cos 2\omega t + \frac{\alpha}{\pi} \sin 2\omega t)\ \omega\ L_{as}\ I_s \tag{28}$$

As before, if $\frac{\alpha}{\pi}$ is disregarded, Equation 28 reduces to

$$v_{ta} = I_a\ (r_a + \frac{\omega\ L_{aa}}{\pi}) - \omega\ L_{as}\ I_s\ \cos 2\omega t \tag{29}$$

The result obtained in Equation 28 or in its simplified version in Equation 29 is rather disfavoring. It implies that the input current from d.c. source will have an alternating component of twice the system frequency, in addition to the constant d.c. component. This imposes an approximation to the above analysis, since we assumed the input current to be constant. In the analysis of two-phase transverter presented below, it will be shown that input current remains purely d.c. even on load. This eliminates the approximation involved in the single-phase analysis.

Two-Phase Transverter

The analysis of the two-phase machine is based along the same lines as that of the single-phase machine. As a matter of fact, some of the equations developed in the last section are used here without any change. The following is the list of additional symbols required in this analysis:

i_{s_1} - Instantaneous (a.c.) current in the stator phase 1.

I_{s_1} - Maximum value of the stator phase 1 current.

i_{s_2} - Instantaneous (a.c.) current in the stator phase 2.

I_{s_2} - Maximum value of the stator phase 2 current.

L_{s_1} - Stator phase 1 self-inductance.

L_{s_2} - Stator phase 2 self-inductance.

ℓ'_{as_1} - Mutual-inductance between non-commutating armature conductors and the stator phase 1 as a function of the position of the brushes.

L'_{as_1} - Maximum value of ℓ'_{as_1}.

ℓ'_{as_2} - Mutual-inductance between non-commutating armature conductors and the stator phase 2 as a function of the position of the brushes.

L'_{as_2} - Maximum value of ℓ'_{as_2}.

L_{as_1} - Mutual-inductance between stator phase 1 and the entire armature winding.

L_{as_2} - Mutual-inductance between stator phase 2 and the entire armature winding.

ℓ_{cs_1} - Mutual-inductance between commutating armature conductors and the stator phase 1 as a function of the position of the brushes.

L_{cs_1} - Maximum value of ℓ_{cs_1}.

ℓ_{cs_2} - Mutual-inductance between commutating armature conductors and the stator phase 2 as a function of the brush position.

L_{cs_2} - Maximum value of ℓ_{cs_2}.

L_{12} - Mutual-inductance between stator phases 1 and 2.

r_{s_1} - Stator phase 1 resistance.

r_{s_2} - Stator phase 2 resistance.

v_{s_1} - Voltage induced in stator phase 1.

v_{s_2} - Voltage induced in stator phase 2.

v_{st_1}, v_{st_2} - Stator terminal voltage of phases 1 and 2 respectively.

ϕ_1, ϕ_2 - Phase angle of i_{s_1} and i_{s_2} with reference to v_{s_1} and v_{s_2} respectively.

Consider the stator winding alone when connected across a two-phase a.c. source as shown in Figure 6.

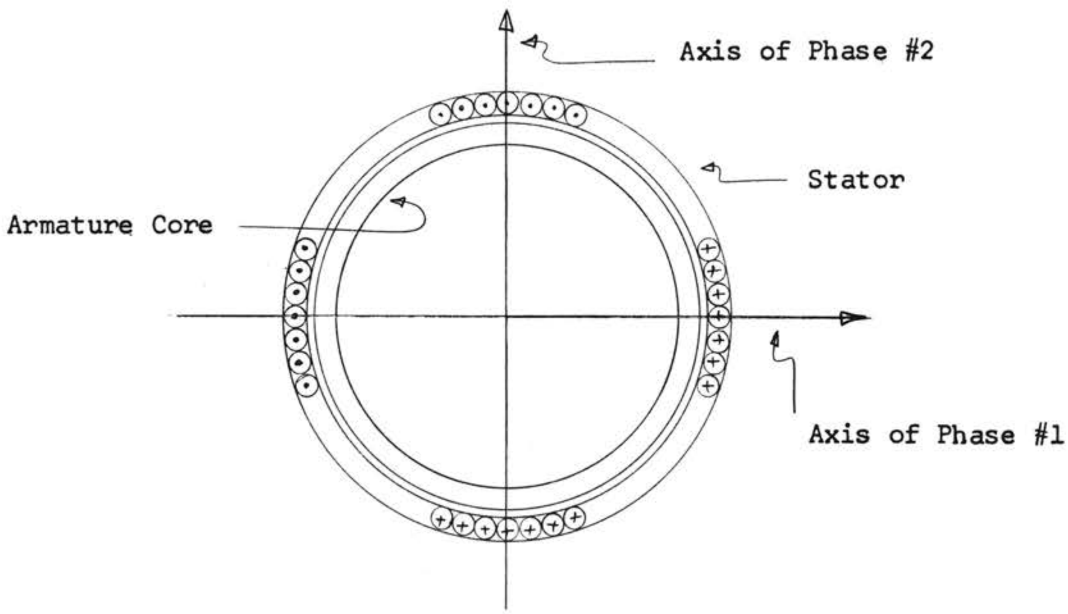

Figure 6. Two-Phase Stator Winding

The terminal voltage equations will be

$$v_{ts_1} = i_{s_1} r_{s_1} + \frac{d}{dt} (L_{s_1} i_{s_1} \pm L_{12} i_{s_2}) \tag{30}$$

$$v_{ts_2} = i_{s_2} r_{s_2} + \frac{d}{dt} (L_{s_2} i_{s_2} \pm L_{12} i_{s_1}) \tag{31}$$

The axes of the two stator phases are mutually orthogonal; therefore, their mutual inductance will be zero. Also since L_{s1} and L_{s2} are constant, Equations 30 and 31 reduce to:

$$v_{ts1} = i_{s1} r_{s1} + L_{s1} \frac{di_{s1}}{dt} \qquad (32)$$

$$v_{ts2} = i_{s2} r_{s2} + L_{s2} \frac{di_{s2}}{dt} \qquad (33)$$

Figure 7 illustrates the two-phase transverter with the brushes rotated through an angle θ with respect to the axis of stator phase 1, which will be taken as reference in the subsequent discussion.

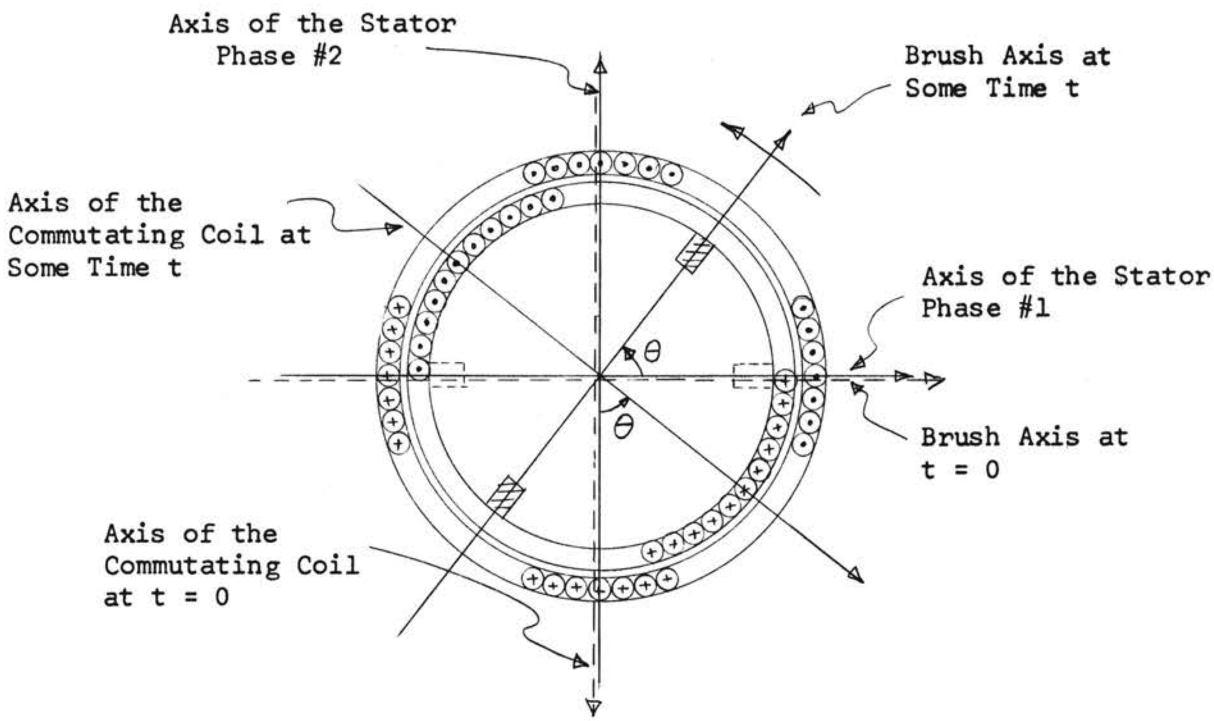

Figure 7. Schematic Diagram of Two-Phase Transverter

Equation 7 is still valid for armature terminal voltage. If the stator winding is open-circuited, the equations of the voltage in this winding may be written as follows:

$$v_{s_1} = \frac{d}{dt}(\ell'_{as_1} i_a + \ell_{cs_1} i_c) \tag{34}$$

$$v_{s_2} = \frac{d}{dt}(\ell'_{as_2} i_a + \ell_{cs_2} i_c) \tag{35}$$

From Figure 7:

$$\ell'_{as1} = L'_{as_1} \cos \theta$$

$$= L'_{as1} \cos \omega t \tag{36}$$

$$\ell'_{as2} = L'_{as2} \cos (\frac{\pi}{2} - \theta)$$

$$= L'_{as2} \sin \omega t \tag{37}$$

and

$$\ell_{cs_1} = L_{cs1} \cos (\frac{\pi}{2} - \theta)$$

$$= L_{cs1} \sin \omega t \tag{38}$$

$$\ell_{cs_2} = L_{cs_2} \cos (\pi - \theta)$$

$$= -L_{cs_2} \cos \omega t \tag{39}$$

Again assuming uniform distribution of the armature and stator windings:

$$L'_{as_1} = \frac{\pi - \alpha}{\pi} L_{as_1} \quad (40)$$

$$L'_{as_2} = \frac{\pi - \alpha}{\pi} L_{as_2} \quad (41)$$

$$L_{cs_1} = \frac{\alpha}{\pi} L_{as_1} \quad (42)$$

$$L_{cs_2} = \frac{\alpha}{\pi} L_{as_2} \quad (43)$$

If we further assume that the stator winding is symmetrical, then

$$L_{as_1} = L_{as_2} = L_{as} \quad (44)$$

Therefore,

$$L'_{as_1} = L_{as_2} = \frac{\pi - \alpha}{\pi} L_{as} \quad (45)$$

$$L_{cs_1} = L_{cs_2} = \frac{\alpha}{\pi} L_{as} \quad (46)$$

By a similar analysis

$$L_{s_1} = L_{s_2} = L_s \quad (47a)$$

$$r_{s_1} = r_{s_2} = r_s \quad (47b)$$

From Equations 34, 36, 38, 40, and 44:

$$v_{s_1} = \frac{\pi - \alpha}{\pi} L_{as} \cos \omega t \frac{di_a}{dt} + i_a \frac{d}{dt} \left(\frac{\pi - \alpha}{\pi} L_{as} \cos \omega t\right) + \frac{\alpha}{\pi} L_{as} \sin \omega t \frac{di_c}{dt} + i_c \frac{d}{dt} \left(\frac{\alpha}{\pi} L_{as} \sin \omega t\right) \quad (48)$$

But

$$\frac{di_a}{dt} = 0 \ ,$$

$i_a = I_a$ being constant. Therefore from Equations 6 and 48:

$$v_{s1} = -I_a \frac{\pi - \alpha}{\pi} L_{as} \ \omega \sin \omega t + \frac{\alpha}{\pi} L_{as} \sin \omega t \frac{I_a \ \omega}{\alpha} + i_c \frac{\alpha}{\pi} L_{as} \ \omega \cos \omega t$$

$$= -(1 - \frac{1 + \alpha}{\pi}) \ I_a \ L_{as} \ \omega \sin \omega t + \frac{\alpha}{\pi} \ i_c \ L_{as} \ \omega \cos \omega t \qquad (49)$$

Disregarding α/π as before,

$$v_{s_1} = - \frac{\pi - 1}{\pi} I_a \ L_{as} \ \omega \sin \omega t \qquad (50)$$

Similarly from Equations 35, 37, 39, 41, and 44

$$v_{s_2} = \frac{\pi - \alpha}{\pi} L_{as} \sin \omega t \frac{di_a}{dt} + i_a \frac{d}{dt} (\frac{\pi - \alpha}{\pi} \ L_{as} \sin \omega t) -$$

$$\frac{\alpha}{\pi} L_{as} \cos \omega t \frac{di_c}{dt} - i_c \frac{d}{dt} (\frac{\alpha}{\pi} \ L_{as} \cos \omega t) \qquad (51)$$

From Equations 6 and 48:

$$v_{s_2} = \frac{\pi - \alpha}{\pi} I_a \ L_{as} \ \omega \cos \omega t - \frac{\alpha}{\pi} L_{as} \cos \omega t \frac{I_a \ \omega}{\alpha} + i_c \frac{\alpha}{\pi} L_{as} \ \omega \sin \omega t$$

$$= (1 - \frac{1 + \alpha}{\pi}) \ I_a \ L_{as} \ \omega \cos \omega t + \frac{\alpha}{\pi} i_c \ L_{as} \ \omega \sin \omega t \qquad (52)$$

Neglecting α/π

$$v_{s_2} = (\frac{\pi - 1}{\pi}) \ I_a \ L_{as} \ \omega \cos \omega t \qquad (53)$$

v_{s_1} and v_{s_2} are also the terminal voltages on no-load.

Equations 50 and 53 suggest that if a load is connected across the stator terminal, a sinusoidal current will result. Keeping Equations 50 and 53 in view, assume

$$i_{s_1} = - I_{s1} \sin (\omega t - \phi_1) \tag{54}$$

$$i_{s_2} = I_{s_2} \cos (\omega t - \phi_2) \tag{55}$$

Consider now the effect of loading the transverter on the a.c. side. The currents i_{s_1} and i_{s_2} give rise to additional flux linkages

$$\ell'_{as_1} i_{s_1} + \ell_{as_2} i_{s_2} + \ell_{cs_1} i_{s_1} + \ell_{cs_2} i_{s2}$$

Taking account of this, Equation 7, which is as good for two-phase transverter as for one with single phase , changes to

$$v_{ta} = I_a \left(r_a + \frac{\omega L_{aa}}{\pi}\right) + \frac{d}{dt} [i_{s_1} (\ell'_{as_1} + \ell_{cs_1}) + i_{s2} (\ell'_{as2} + \ell_{cs2})] \tag{56}$$

For clarity each term in the square parentheses will be considered separately.

From Equations 36, 40, and 54:

$$\frac{d}{dt} (i_{s_1} \ell'_{as_1}) = -I_{s1} \sin (\omega t - \phi_1) \frac{d}{dt} \left(\frac{\pi - \alpha}{\pi} L_{as_1} \cos \omega t\right) +$$

$$\frac{\pi - \alpha}{\pi} L_{as_1} \cos \omega t \frac{d}{dt} \left(-I_{s_1} \sin (\omega t - \phi_1)\right)$$

$$= I_{s1} \sin (\omega t - \phi_1) \frac{\pi - \alpha}{\pi} \omega L_{as_1} \sin \omega t -$$

$$I_{s_1} \frac{\pi - \alpha}{\pi} \omega L_{as_1} \cos \omega t \cos (\omega t - \phi_1)$$

$$= \frac{\pi - \alpha}{\pi} I_{s_1} \omega L_{as_1} [\sin(\omega t - \phi_1) \sin \omega t - \cos(\omega t - \phi_1) \cos \omega t]$$

$$= - \frac{\pi - \alpha}{\pi} I_{s1} \omega L_{as1} \cos(2\omega t - \phi_1) \tag{57}$$

From Equations 44 and 57:

$$\frac{d}{dt}(i_{s1} \ell'_{as1}) = - \frac{\pi - \alpha}{\pi} I_{s_1} \omega L_{as} \cos(2\omega t - \phi_1) \tag{58}$$

From Equations 37, 41, and 55:

$$\frac{d}{dt}(i_{s_2} \ell'_{as_2}) = I_{s_2} \cos(\omega t - \phi_2) \frac{d}{dt}\left(\frac{\pi - \alpha}{\pi} L_{as_2} \sin \omega t\right) + \frac{\pi - \alpha}{\pi} L_{as_2} \sin \omega t \frac{d}{dt}\left(\cos(\omega t - \phi_2)\right)$$

$$= \frac{\pi - \alpha}{\pi} I_{s_2} \omega L_{as_2} \cos(\omega t - \phi_2) \cos \omega t - \frac{\pi - \alpha}{\pi} I_{s_2} \omega L_{as_2} \sin(\omega t - \phi_2) \sin \omega t$$

$$= \frac{\pi - \alpha}{\pi} I_{s_2} \omega L_{as_2} [\cos(\omega t - \phi_2) \cos \omega t - \sin(\omega t - \phi_2) \sin \omega t]$$

$$= \frac{\pi - \alpha}{\pi} I_{s_2} \omega L_{as_2} \cos(2\omega t - \phi_2) \tag{59}$$

From Equations 44 and 59:

$$\frac{d}{dt}(i_{s_2}\ \ell'_{as_2}) = \frac{\pi - \alpha}{\pi} I_{s_2}\ \omega\ L_{as} \cos(2\omega t - \phi_2) \quad (60)$$

From Equations 38, 42, and 54:

$$\frac{d}{dt}(i_{s_1}\ \ell_{cs_1}) = -I_{s_1} \sin(\omega t - \phi_1) \frac{d}{dt}(\frac{\alpha}{\pi} L_{as_1} \sin \omega t) +$$

$$\frac{\alpha}{\pi} L_{as_1} \sin \omega t \frac{d}{dt}\left(-I_{s_1} \sin(\omega t - \phi_1)\right)$$

$$= -\frac{\alpha}{\pi} I_{s_1}\ \omega\ L_{as_1} \sin(\omega t - \phi_1) \cos \omega t -$$

$$\frac{\alpha}{\pi} I_{s_1}\ \omega\ L_{as_1} \cos(\omega t - \phi_1) \sin \omega t$$

$$= -\frac{\alpha}{\pi} I_{s_1}\ \omega\ L_{as_1} \sin(2\omega t - \phi_1) \quad (61)$$

From Equations 44 and 61:

$$\frac{d}{dt}(i_{s_1}\ \ell_{cs_1}) = -\frac{\alpha}{\pi} I_{s_1}\ \omega\ L_{as} \sin(2\omega t - \phi_1) \quad (62)$$

From Equations 39, 43, and 55:

$$\frac{d}{dt}(i_{s_2}\ \ell_{cs_2}) = I_{s_2} \cos(\omega t - \phi_2) \frac{d}{dt}(-\frac{\alpha}{\pi} L_{as_2} \cos \omega t) -$$

$$\frac{\alpha}{\pi} L_{as_2} \cos \omega t \frac{d}{dt}\left(I_{s_2} \cos(\omega t - \phi_2)\right)$$

$$= \frac{\alpha}{\pi} I_{s_2}\ \omega\ L_{as_2} \cos(\omega t - \phi_2) \sin \omega t +$$

$$\frac{\alpha}{\pi} I_{s_2}\ \omega\ L_{as_2} \sin(\omega t - \phi_2) \cos \omega t$$

$$= \frac{\alpha}{\pi} I_{s_2}\ \omega\ L_{as_2} \sin(2\omega t - \phi_2) \quad (63)$$

From Equations 44 and 63:

$$\frac{d}{dt}\,(i_{s_2}\,\ell_{cs_2}) = \frac{\alpha}{\pi}\, I_{s_2}\,\omega\, L_{as}\,\sin\,(2\omega t - \phi_1) \tag{64}$$

Adding Equations 58 and 60

$$\frac{d}{dt}\,(i_{s_1}\,\ell'_{as_1}) + \frac{d}{dt}\,(i_{s_2}\,\ell'_{as2}) = -\,\frac{\pi - \alpha}{\pi}\,\omega\, L_{as}\,[I_{s_1}\cos\,(2\omega t - \phi_1) - I_{s_2}\cos\,(2\omega t - \phi_2)] \tag{65}$$

Adding Equations 62 and 64

$$\frac{d}{dt}\,(i_{s_1}\,\ell_{cs_1}) + \frac{d}{dt}\,(i_{s_2}\,\ell_{cs_2}) = -\,\frac{\alpha}{\pi}\,\omega\, L_{as}\,[I_{s_1}\sin\,(2\omega t - \phi_1) - I_{s_2}\sin\,(2\omega t - \phi_2)] \tag{66}$$

Therefore from Equations 56, 65, and 66:

$$v_{ta} = I_a\,(r_a + \frac{\omega\, L_{aa}}{\pi}) - \frac{\pi - \alpha}{\pi}\,\omega\, L_{as}\,[I_{s_1}\cos\,(2\omega t - \phi_1) - I_{s_2}\cos\,(2\omega t - \phi_2)] - \frac{\alpha}{\pi}\,\omega\, L_{as}\,[I_{s_1}\sin\,(2\omega t - \phi_1) - I_{s_2}\sin\,(2\omega t - \phi_2)] \tag{67}$$

Equation 67 is suggestive to assume balanced loading, in which case

$$I_{s1} = I_{s_2},\quad \phi_1 = \phi_2 \tag{68}$$

Then from Equation 65 and 68:

$$\frac{d}{dt}\,(i_{s_1}\,\ell'_{as_1}) + \frac{d}{dt}\,(i_{s_2}\,\ell'_{as_2}) = 0 \tag{69}$$

And from Equations 66 and 68

$$\frac{d}{dt}(i_{s_1} \ell_{cs_1}) + \frac{d}{dt}(i_{s_2} \ell_{cs_2}) = 0 \tag{70}$$

Hence for balanced loading

$$v_{ta} = I_a \left(r_a + \frac{\omega L_{aa}}{\pi}\right) \tag{71}$$

For unbalanced loads, the machine will behave similar to the single-phase transverter. The input current from the d.c. source will have an alternating component of twice the system frequency in addition to the direct component.

Finally, consider the effect of loading on the output terminal voltage. For phase 1

$$v_{ts_1} = v_{s_1} - i_{s_1} r_{s_1} - \frac{d}{dt}(i_{s_1} L_{s_1}) \tag{72}$$

From Equations 54 and 72:

$$v_{ts_1} = v_{s_1} + I_{s_1} r_{s_1} \sin(\omega t - \phi_1) + L_{s_1} I_{s_1} \omega \cos(\omega t - \phi_1) \tag{73}$$

From Equations 47a, 47b, 50, and 72:

$$v_{ts_1} = - \frac{\pi - 1}{\pi} I_a L_{as} \omega \sin \omega t + I_{s_1} [r_s \sin(\omega t - \phi_1) + \omega L_s \cos (\omega t - \phi_1)] \tag{74}$$

Similarly for phase 2

$$v_{ts_2} = v_{s_2} - i_{s_1} r_{s_2} - \frac{d}{dt}(i_{s_2} L_{s_2}) \tag{75}$$

From Equations 55 and 75:

$$v_{ts_2} = v_{s_2} - I_{s_2} r_{s_2} \cos(\omega t - \phi_2) + L_{s_2} I_{s_2} \omega \sin(\omega t - \phi_2) \quad (76)$$

From Equations 47a, 47b, 53, and 75:

$$v_{ts_2} = \frac{\pi - 1}{\pi} I_a \omega L_{as} \cos \omega t - I_{s_2} [r_s \cos(\omega t - \phi_2) - \omega L_s \sin(\omega t - \phi_2)] \quad (77)$$

Assuming a balanced load,

$$I_{s1} = I_{s_2} = I_s \quad (78)$$

$$\phi_1 = \phi_2 = \phi \quad (79)$$

From Equations 74, 77, 78, and 79:

$$v_{ts1} = -\frac{\pi - 1}{\pi} I_a L_{as} \omega \sin \omega t + I_s [r_s \sin(\omega t - \phi) + \omega L_s \cos(\omega t - \phi)] \quad (80)$$

$$v_{ts_2} = \frac{\pi - 1}{\pi} I_a L_{as} \omega \cos \omega t - I_s [r_s \cos(\omega t - \phi) - \omega L_s \sin(\omega t - \phi)] \quad (81)$$

This completes the mathematical analysis of the transverter for voltage transformation. As indicated earlier, torque and power transformation are not considered in this thesis.

CHAPTER IV

EXPERIMENTAL WORK AND OBSERVATIONS

An experimental investigation was made on the Westinghouse Electric Corporation Generalized Machine to verify the results of the mathematical analysis in Chapter III. This machine which is generalized in its true sense was not ideal to work as a transverter. Yet, it could be arranged to demonstrate the principles involved in a transverter fairly successfully.

Generalized Machine

The purpose here is not to give the complete description of the Generalized Machine, but just to outline the parts and parameters involved in the demonstration of this study.

(i) <u>Stator</u>

The stator has a standard two-pole, two-phase distributed winding. Each phase in itself has two windings which could be connected in series or in parallel. In this case the windings were connected in series. Stator per phase resistance is 2.8 ohms and per phase self-inductance, 0.40 henries. Maximum rated load for the stator with series connection is 230 volts and 3.6 amps.

(ii) <u>Rotor</u>

The rotor is standard two-pole, continuous lap wound armature with commutator. The rotor winding resistance is 0.46 ohms and its self-inductance, 0.05 henries. Four commutator brushes are symmetrically mounted on a special design rotating brush carriage (in the present case only two brushes were used). The commutator brushes are connected to separate slip rings on the brush carriage shaft to provide the brush terminals. Brush contact resistance is given to be 2 ohms at 2 amperes. d.c.

Stator-to-rotor mutual inductance with stator winding connected in series for maximum coupling is 0.15 henries.

(iii) Brush Carriage and Drive Motor

The brush carriage drive motor is a 1/4 horsepower d.c. shunt motor. Maximum allowable speed of this motor is 1,800 rpm.

The rotor and brush carriage are coaxial and can be driven independently. Either one can be locked in any position relative to the frame; in this experiment the rotor was locked. A schematic diagram of the Generalized Machine is shown in Figure 8.

Experimental Procedure

Figure 9 illustrates the experimental setup of the transverter.

(1) With the output terminals A-N, B-N open, brushes were run at different speeds. The relation between input current and voltage was studied. The wave shape of the output voltage across A-N and B-N was observed on a double-beam oscilloscope.

(2) A variable resistance load was connected across A-N (Figure 9). Its effect on the input voltage and current was

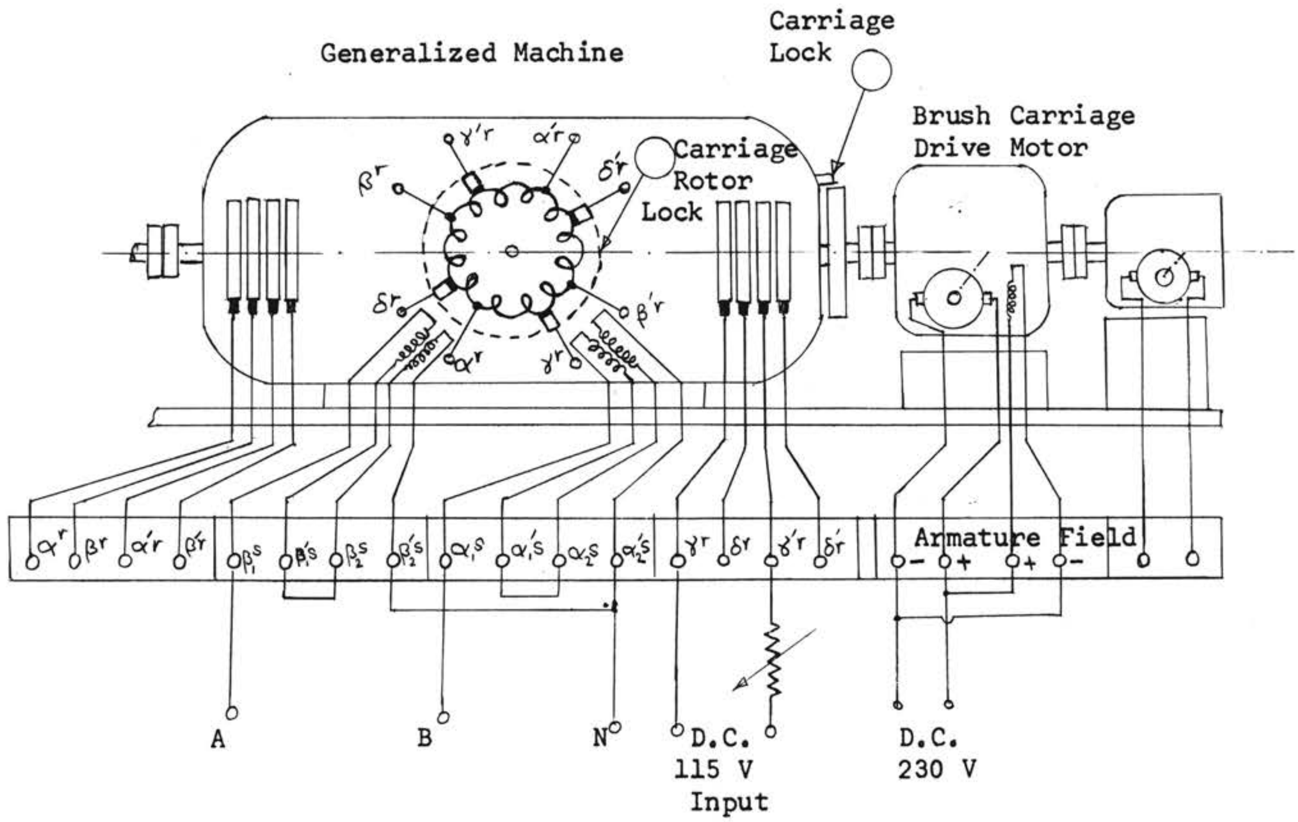

Figure 8. Schematic Diagram of the Generalized Machine Laboratory Set

studied. Input voltage and current waveforms were observed.

(3) Part 2 was repeated with balanced and unbalanced loads across terminals A-N and B-N.

(4) A 1/4 horsepower three-phase induction motor was used to study the behavior of the transverter under reactive loads. Three-phase voltage was obtained by means of a two-phase/three-phase scott-connected transformer.

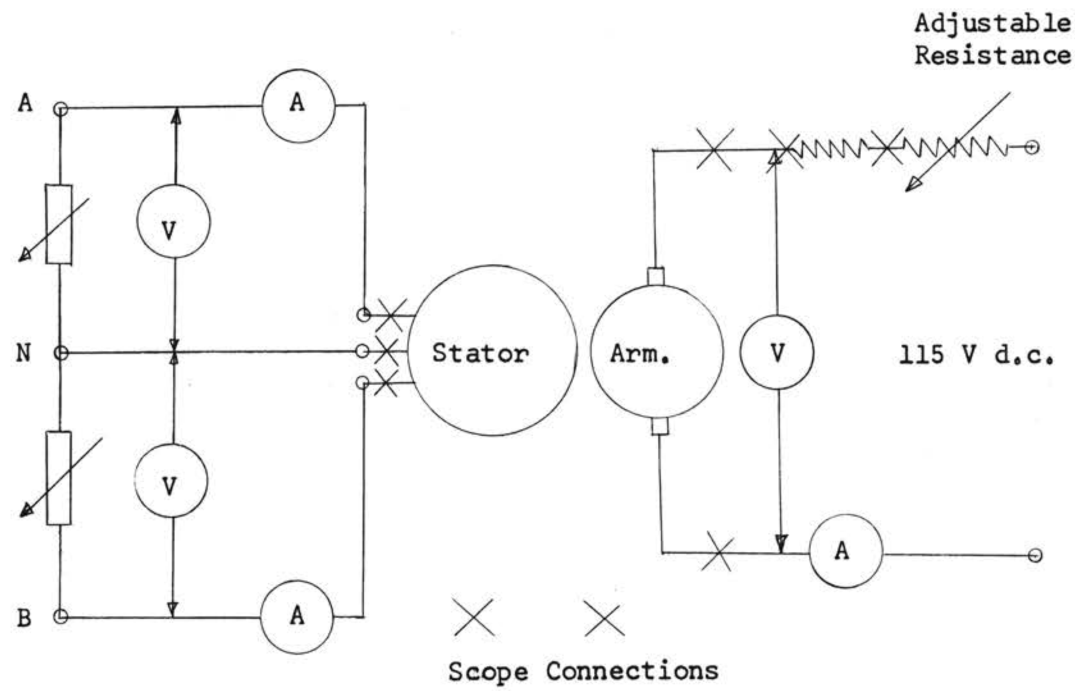

Figure 9. Experimental Transverter Setup

Observations

It is suspected that the value of brush contact resistance as given in the Westinghouse Manual is not very accurate. It was found that this resistance is maximum when the brushes are stationary and decrease with increase in speed. In any case, it is greater than the given value of two ohms.

The wave shapes of different quantities as observed on the oscilloscope are shown in Figure 10. The frequency of oscillation corresponds to the speed of the brushes.

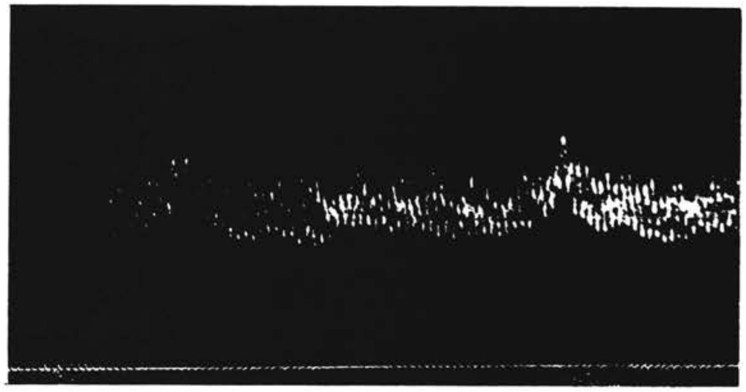

Figure 10a. Input Voltage on No-Load

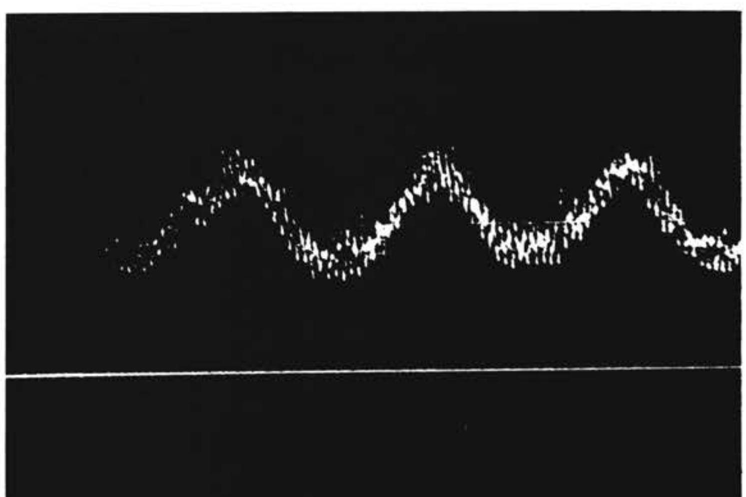

Figure 10b. Input Voltage with One Phase Loaded

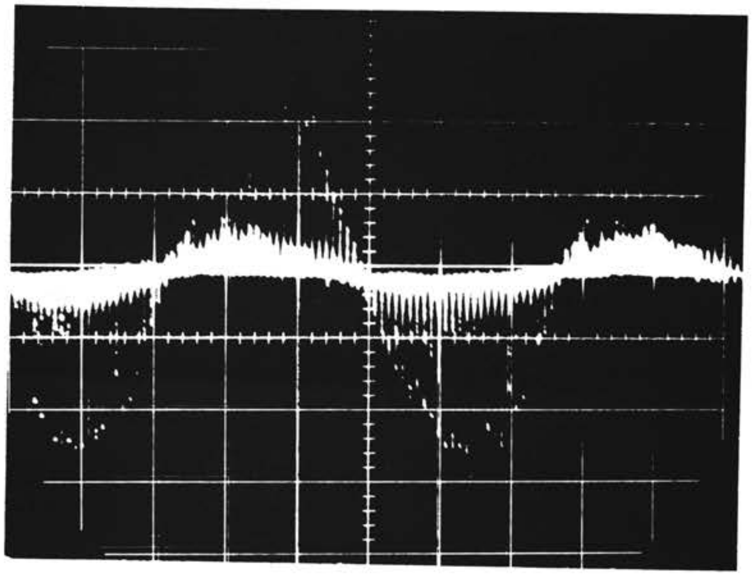

Figure 10c. Output Voltage Across A-N on No-Load

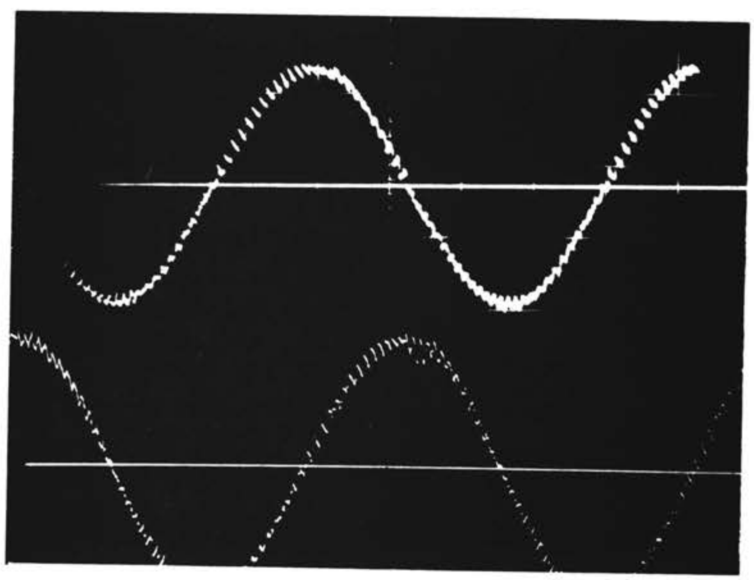

Figure 10d. Output Voltage Across A-N (Top), Across B-N (Bottom) with Balanced Load on the Two Phases

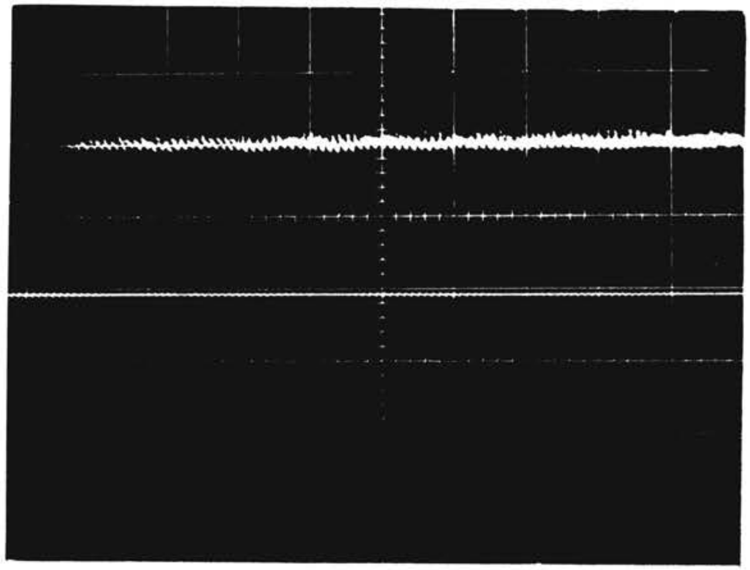

Figure 10e. Input Current on No-Load

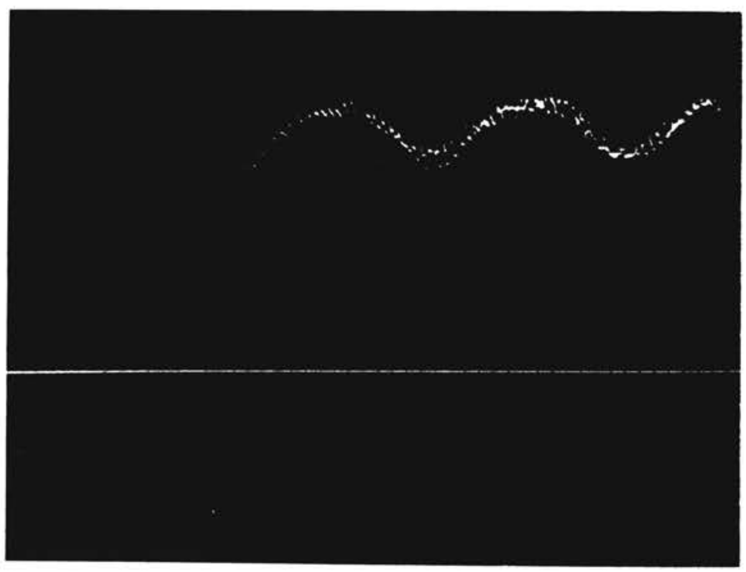

Figure 10f. Input Current with Only One Phase Loaded

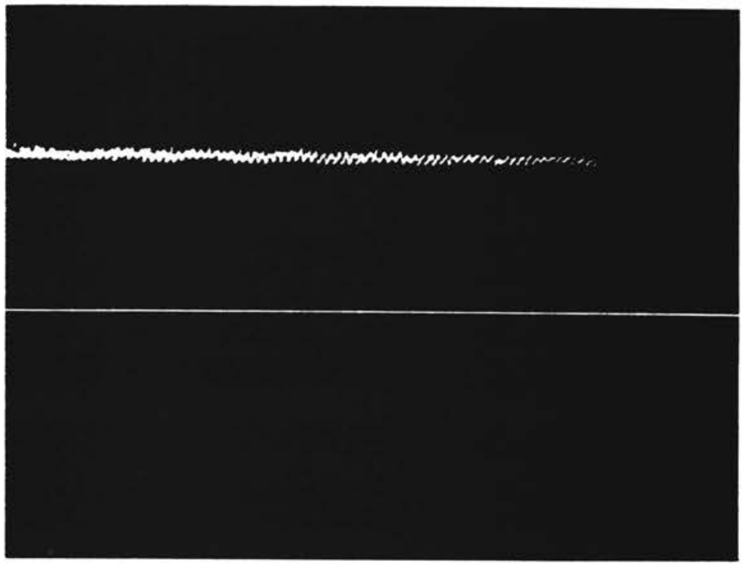

Figure 10g. Input Current with Balanced Load
Across the Two Phases

Throughout the experiment, the brushes were kept running at a constant speed of 1,100 rpm. Time scale of the oscilloscope was fixed at 10 ms./cm. Vertical deflection scale and the control and load rheostats were adjusted to get matching size pictures.

A three-phase induction motor was used as a load for curiosity. With this inductive load, nothing particularly important was observed. The motor was running as if connected to any other low voltage three-phase a.c. source.

It is important to note that heavy sparking was taking place when armature current was aroung 4 amperes.

CHAPTER V

DISCUSSION OF THE RESULTS

In the mathematical analysis, brush contact resistance is not considered separately. Here r_a represents both internal resistance of the armature and the brush contact resistance. In Equation 7 $I_a r_a$ is the voltage drop in the armature circuit resistance, and $I_a \omega L_{aa}/\pi$ is the voltage that is being transferred to the other side. For the Generalized Machine, r_a is almost three times as much as $\omega L_{aa}/\pi$ at 1,100 rpm, which shows the extent by which this machine is inefficient to work as a transverter. The brushes could not be run at higher speeds to increase ωL_{aa} because of sparking problem. A more systematic experimental study was handicapped by the fact that the brush contact resistance was not constant for different values of armature current and brush speed. The adjustable resistance in the input circuit used to limit the armature current was also felt very inconvenient. This could be avoided if a low voltage d.c. source were available.

D.C. voltage for the experiment was obtained from a motor-generator set. Even though this voltage is fairly smooth, the input voltage across the armature when the brushes are rotating is very oscillatory (Figure 10a), especially when the input current is around 4 amperes. This is due to heavy sparking. It is suspected that the brushes were not making good contact with the commutator segments. These oscillations which are high frequency in nature are absent from the input current (Figure 10e), as can be expected.

On no-load, as can be seen from Figure 10c, the output voltage though sinusoidal is very impulsive. This is typical of all devices where commutator is used and need not be commented on here. These impulses disappear when the machine is loaded (Figure 10d).

The effect of single-phase loading, which is a special case of unbalanced loading, is shown in Figure 10b. As predicted by Equation 29 or Equation 67, the voltage across the armature terminals contain an alternating component of twice the system frequency. The same is true about the input current (Figure 10f). As before, the high frequency oscillations which are present in voltage wave are absent to a great extent from the current wave.

Input current and voltage wave shapes with balanced loading are the same as on the no-load. This is also in agreement with Equation 71 derived in Chapter III.

CHAPTER VI

CONCLUSIONS

The primary objective of this study was to investigate the possibility of making a static electromagnetic device which could do the job of rectification and inversion. A thorough mathematical analysis of such a device has been presented in the preceding pages. The necessity of a brush carriage drive motor should not lead one to believe that the transverter is not a static device. As stated previously, this motor is just an accessory and in a properly designed transverter, power consumed by this motor can be almost negligible compared to the power handled by the transverter itself.

The transverter demands its own specifications. As can be seen from armature input and stator output voltage equations, high armature self-inductance and high mutual-inductance between armature and stator are required. Of course, as in any other machine, low internal resistance is desirable. Since there is no relative motion between the armature and the stator, the air gap can be avoided completely. This will aid in increasing the inductances. For the armature winding, many turns of smaller cross-section will be more useful than few turns of larger cross-section. Increasing the number of turns will increase the inductance, and smaller cross-section implies small armature current, which in turn improves commutation.

For a.c. to d.c. conversion, a synchronous brush carriage drive motor is essential.

As a by-product of this study, a suggestion can be made for a new type of phase converter transformer. In the above machine (transverter), if the armature winding is replaced by a single-phase alternator stator winding, then it is conceivable that for multi-phase input, the output across this (single-phase stator) winding will be of single phase. Of course, in this case no commutator or brushes are required.

This study by no means covers all the aspects of the transverter. The design suggestions made above are the essential requirements for a better experimental model to carry out further investigations. For example, power transformation from one winding to the other is not considered here. Before this is done, it cannot be decided whether this device is practical or not. Thus, it is felt that this is a fertile area for further research.

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