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Computer Simulation of an Induction Machine with Spatially Dependent Saturation

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COMPUTER SIMULATION OF AN INDUCTION MACHINE WITH SPATIALLY DEPENDENT SATURATION

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Abstract

This paper presents a new analog computer model for the simulation of an induction machine which takes into account the spatially dependent main flux saturation effect. Using this model of saturation, an unstable operating region for a voltage fed induction motor with high source impedance has been calculated and has been correlated with both test results and the results predicted by the conventional linearized model. This study clearly demonstrates an improvement over the linearized model in predicting machine dynamic behavior. Because the simulation accurately models large signal as well as small signal behavior it should prove equally useful in predicting transient behavior. The manner of dealing with saturation of the magnetizing field presented in this paper can be readily implemented on a digital as well as an analog computer and can also be extended to the study of other electrical machines.

Introduction

Accurate prediction of transient (large signal) and dynamic (small signal) performance is a valuable tool in the development of induction machine drive systems. Considerable effort has been directed toward improved computer models owing to the fact that transient and dynamic behavior of induction motor drive systems is often an important application consideration. Models simulated by digital or analog computers have been proposed to predict the performance of most drive systems.[1-5] Such models have proven to be extremely successful in predicting the trends observed in actual systems. However, in certain cases these models have not predicted dynamic behavior with acceptable accuracy, particularly in the study of dynamic instabilities.[6-7]

For a considerable time, it has been observed that the theoretical instability region predicted by a conventional linearized model is more conservative than actually observed in practical applications. Experiments indicate that a machine may be stable even if its operating condition corresponds to a theoretically unstable state predicted by the conventional linearized model.[8] There are, of course, many factors which cause discrepancies, such as skin effect, iron losses, mechanical damping and so forth. However, the effect of saturation in the main magnetizing field has long been suspected as a major cause for the disparity between theory and experiment. In the past, a number of schemes have been proposed to model saturation but have had limited success in predicting instability.[9-11] Recently, however, a digital computer model of a sinusoidal voltage driven induction machine including spatially dependent main flux saturation was experimentally proven to predict instability regions associated with resistive source impedance with excellent correlation.[12,13] However, the approach that was utilized employed linearization techniques so that it is valid only for small changes about an equilibrium. Clearly, large signal transients are equally as important as small changes about an operating point. The means to correctly incorporate the spatially dependent saturation of the main magnetizing field into a conventional large signal d-q computer model is the subject of this paper.

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Conventional Model with Constant Parameters

Figure 1 shows the analog computer representation of a conventional constant parameter model in which an induction machine is represented in a rotating d-q axes. A detailed description of the equations which lead up to this simulation is given in Ref. 14. In general, the relevant equations which concern saturation involve the flux linkages and are expressed in d-q variables by

$$\psi_{qs} = x_{\ell s} i_{qs} + \psi_{mq} \quad (1)$$

$$\psi_{ds} = x_{\ell s} i_{ds} + \psi_{md} \quad (2)$$

$$\psi'_{qr} = x'_{\ell r} i'_{qr} + \psi_{mq} \quad (3)$$

$$\psi'_{dr} = x'_{\ell r} i'_{dr} + \psi_{md} \quad (4)$$

where

$$\psi_{mq} = x^*_{mq}\left(\frac{\psi_{qs}}{x_{\ell s}} + \frac{\psi'_{qr}}{x'_{\ell r}}\right) \quad (5)$$

$$\psi_{md} = x^*_{md}\left(\frac{\psi_{ds}}{x_{\ell s}} + \frac{\psi'_{dr}}{x'_{\ell r}}\right) \quad (6)$$

$$x^*_{mq} = x^*_{md} = \frac{1}{\left(\frac{1}{x_m} + \frac{1}{x_{\ell s}} + \frac{1}{x'_{\ell r}}\right)} \quad (7)$$

and where

- ψ_{qs}, ψ_{ds} — q and d axis stator total flux, respectively
- ψ'_{qr}, ψ'_{dr} — q and d axis rotor total flux, respectively
- ψ_{mq}, ψ_{md} — q and d axis magnetizing flux, respectively
- $x_{\ell s}$, $x'_{\ell r}$ — stator and rotor leakage reactance, respectively and
- x_m — magnetizing reactance.

The reactances $x_{\ell s}$, $x'_{\ell r}$, and x_m are reactances defined in terms of the base angular frequency ω_b so that the flux linkages ψ_{qs}, ψ_{ds}, etc. carry the units of volts. Note that the magnetizing reactance x_m appears as a term in the denominator of Eq. 7 so that if treated as a variable the simulation becomes much more difficult to solve.

It is useful to discuss in more detail the determination of magnetizing reactance x_m. A typical magnetizing characteristic of an induction machine is shown in Fig. 2. In general, the definition of the air gap voltage E and magnetizing current I_m of Fig. 2 are given in terms of the equivalent circuit and phasor diagrams of an induction machine, Figs. 3 and 4. In practice three values of magnetizing reactance x_m can be defined on the saturation characteristic:[12,13]

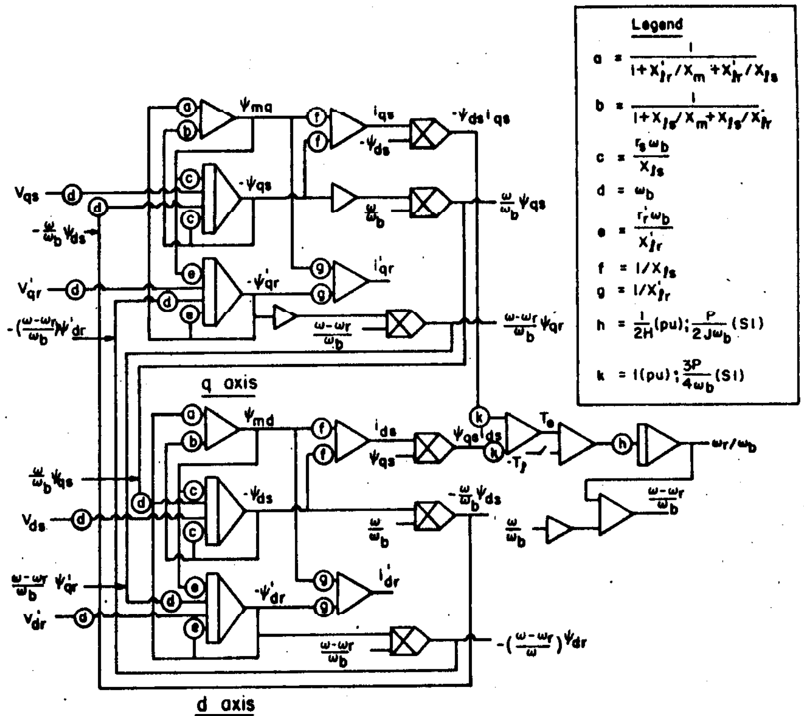

Fig. 1 Analog Computer Simulation Diagram of Conventional Constant Parameter Model.

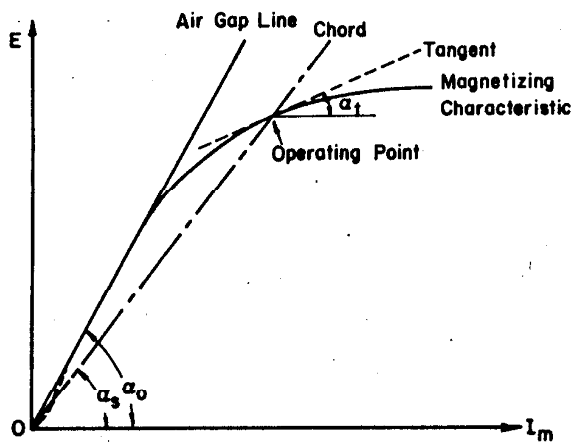

Fig. 2 Magnetizing Characteristic of Induction Motor.

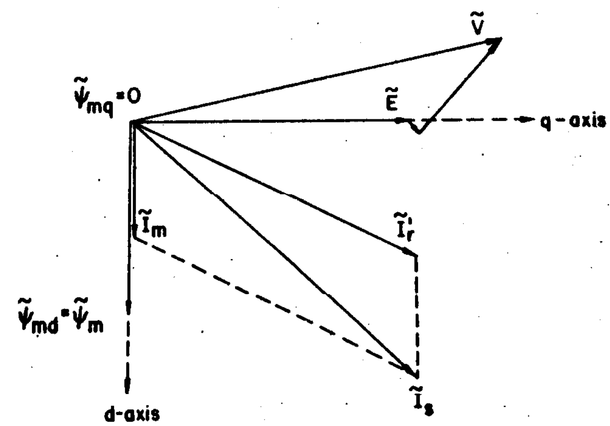

Fig. 4 Steady State Phasor Diagram of Induction Machine.

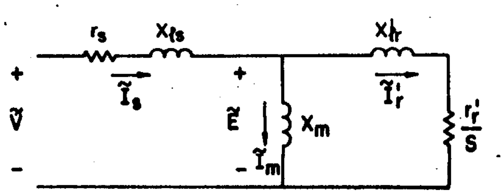

Fig. 3 Per Phase Equivalent Circuit of Induction Machine.

unsaturated magnetizing reactance;

$x_m(\text{unsat}) = \tan(\alpha_0)$

steady state saturated magnetizing reactance;

$x_m(\text{sat}) = \tan(\alpha_s)$

and transient saturated magnetizing reactance;

$x_{mt}(\text{sat}) = \tan(\alpha_t)$,

where α_0 is the angle between abscissa and the air gap line of the magnetizing characteristic,

α_s is the angle between abscissa and the chord which initiates from the origin and passes through the operating point,

α_t is the angle between abscissa and the tangent at the operating point.

It is apparent that only within the unsaturated region will the three magnetizing reactances be the same and for normal load conditions these reactances could assume substantially different values.

If the operating point remains in the saturated region of the magnetizing characteristic, conventional simulation models of saturation incorporate a conventional constant parameter model in which saturated magnetizing reactance $x_m(sat)$ is chosen to typify the degree of saturation encountered. When operation is such that wide excursions of air gap flux are experienced, the magnetizing reactance is then programmed to vary in accordance with the saturation which exists. In either case, changes in magnetizing flux ψ_m or air gap e.m.f. E resulting from perturbations in magnetizing current I_m are forced to occur along the chord slope through the operating point. In practice, however, changes in flux actually occur along the magnetizing characteristic around the operating point. The proper saturated magnetizing reactance, which is truly valid for any time instant, must be calculated from the tangent of the magnetizing characteristic at the operating point. This observation suggests the definition of a so called transient saturated magnetizing reactance $x_{mt}(sat)$.[13]

Typical machines are designed to operate near the "knee" of the magnetizing characteristic where the main flux path begins to saturate and considerable differences may exist between the steady state and transient values of saturated magnetizing reactance. Hence, flux changes will be reduced as the degree of saturation at the operating point increases. Such behavior clearly has an important effect on machine damping and stability and the conventional cord-slope parameter model of magnetizing reactance will clearly lead to discrepancies in the study of dynamic problems. Although the transient saturated magnetizing reactance $x_{mt}(sat)$ can be introduced by means of a simple table look up procedure, such a direct approach leads to enormously increased digital computer computation time or analog computer complexity. A more efficient approach is to model the saturation curve directly so that both small signal and large signal requirements are satisfied implicitly.

Axes Alignment of Saturation Model

In the past, problem solving which concerns both voltge-fed and current-fed induction machines has utilized d,q axis theory with great utility. It has been shown that in many cases it is convenient to align the machine terminal voltage with the q axis of a rotating d,q reference frame. The required equations of transformation to refer system variables to this reference frame are readily deduced since the terminal voltages are usually independent time functions which are explicitly known. In this manner the simulation task often simplifies considerably.[15] Similarly, current-fed machines are often modeled by fixing the d (or q) axis to an explicitly known stator current vector. In either case such manipulation of the machine equations results in a magnetizing current i_m, which has two components i_{mq} and i_{md}. These currents, in turn, result in d and q axis flux components ψ_{mq} and ψ_{md}. When considering the saturation of the magnetizing field, it is clearly necessary to deal with these magnetizing flux components simultaneously since saturation is caused by the instantaneous amplitude of magnetizing current (or MMF) and not by its individual components. As a result, the processing required to achieve the desired saturation effect becomes complex.

It would be useful to consider means for forcing alignment of the magnetizing flux ψ_m with one of d,q axes, say the d axis. In this case one of the two components would be identically equal to the instantaneous flux while its orthogonal companion component would be identically zero. Hence, the saturation effect need be modeled only in the d axis while the usual constant parameter model is used in the q axis since, ideally, the flux in this axis is negligible. Such an axes orientation would clearly simplify the computation. However, the alignment problem is now not so simple since the instantaneous position of the magnetizing current (MMF) vector is not explicitly known as was the case for axes alignment in the voltage-fed and current-fed systems. In order to mechanize a forced alignment of the d axis with the magnetizing flux ψ_m application of feedback control principles is useful. In particular, it can be recalled that when alignment is achieved then $\psi_{mq} = 0$. Hence ψ_{mq} can be viewed as an error signal which must be dynamically zeroed as the simulation equations are solved for a particular transient. A P-I regulator can be implemented in the machine simulation model which regulates ψ_{mq} to zero by dynamically adjusting the alignment of the d,q axes. A block diagram depicting this procedure is shown in Fig. 5, where the quantity $T(\theta)$ expresses the transformation of stator variables to a rotating reference frame.

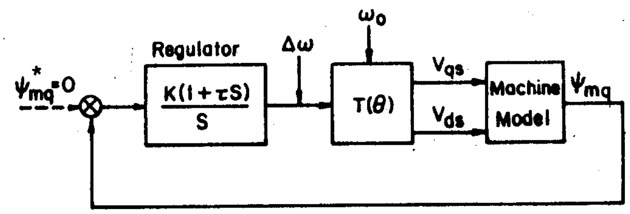

Fig. 5 Block Diagram Illustrating Feedback Scheme for Axes Alignment.

Typical analog computer traces which illustrate free acceleration from rest of a typical induction machine are shown in Figs. 6 and 7. The parameters of the machine chosen are given in the Appendix. In both computer runs the magnetizing reactance was assumed constant. The traces shown in Fig. 6 show a case where the conventional approach is used and the machine terminal voltage V is aligned with the q axis of the reference frame which obviously results in the magnetizing flux having two components. The second trace shows the case where the d axis of the reference frame is forced to align with the magnetizing flux ψ_m. From the trace of ψ_{mq} in Fig. 7 it can be seen that after a single small initial excursion which forces alignment at the start of the solution, the regulator can accurately maintain the desired condition $\psi_{mq} = 0$ during the entire dynamic process. From comparison of the two sets of traces it also can be noted that although there are different values for the same component in the two cases due to different alignment of reference frame, the invariant quantities, such as torque T_e and rotor angular velocity ω_r are identical which is, of course, to be expected.

It should be noted that the proper proportional and integral gain constants are easily determined by trial and error. It appears that positioning of the open loop regulator zero at approximately one tenth the smallest electrical time constant with sufficient gain to ensure closed loop integrator pole migration near to this zero will result in satisfactory behavior. Bode interpretations of the P-I gain constants are also feasible. It appears that arbitrarily large gains are possible. An increasingly small closed loop time constant will, of course, require increasingly small step sizes in the case of digital computation and a practical compromise must typically be reached.

Incorporation of Saturation

Because the q axis flux ψ_{mq} is maintained at zero at all times, it is clear that this component will op-

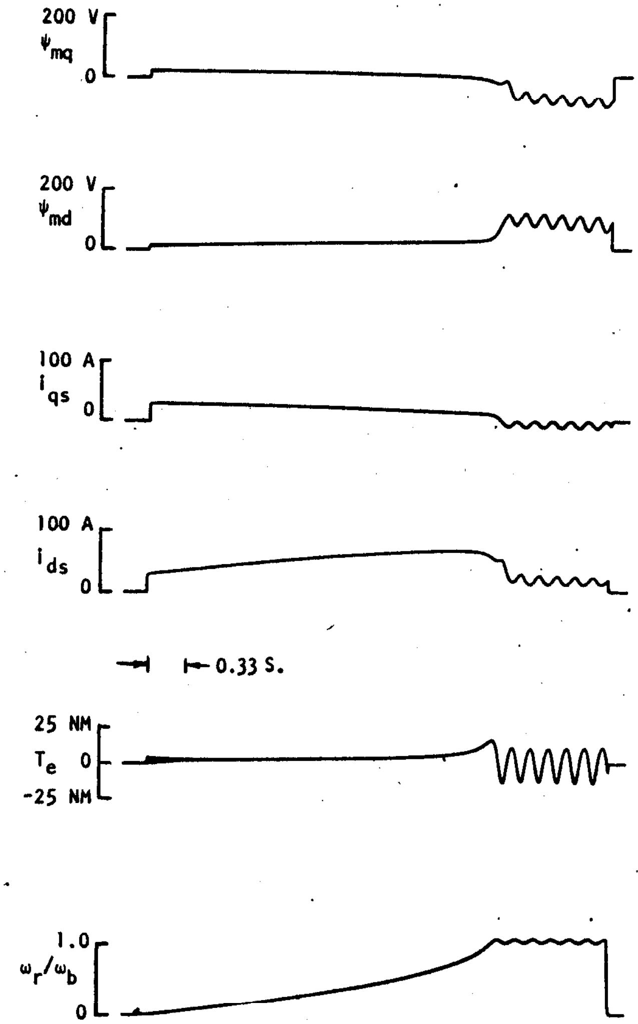

Fig. 6 Analog Computer Traces of Free Acceleration Computed by Aligning Terminal Voltage with the q Axis. Line-to-Line Voltage V_{L-L}= 204 V., Total Stator Resistance $\sum r_s$= 3.48 Ω.

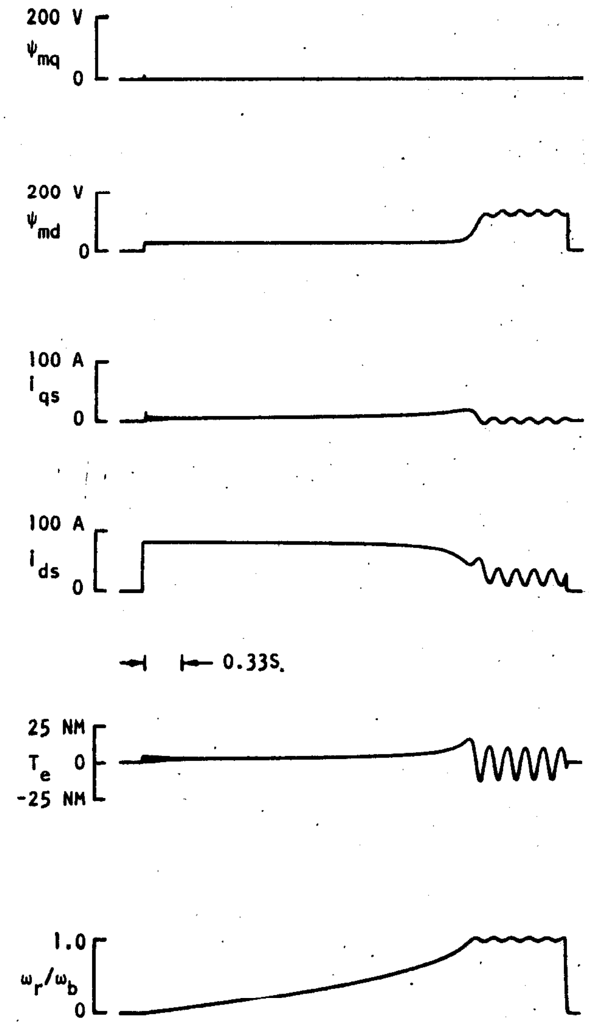

Fig. 7 Analog Computer Traces of Free Acceleration Computed by Forced Alignment of the Magnetizing Flux Vector with the d Axis. Voltage and Stator Resistance as in Fig. 6.

erate near the origin of the magnetizing characteristic. When an infinitesmal change in q axis flux ψ_{mq} occurs, the dynamic process will take place along the initial part of the magnetizing characteristic and the corresponding transient magnetizing reactance should be calculated from the slope of the tangent of the magnetizing characteristic at the origin. Unfortunately, it is difficult to determine the slope in this region. However, it is sufficiently accurate to adopt the slope of the air gap line, i.e. unsaturated magnetizing reactance ψ_m(unsat), as the dynamic reactance for q axis magnetizing field since it has been determined from experimentation that the choice of magnetizing reactance for the unmagnetized q axis circuit has essentially no effect on the computed solution.

In the case of the d axis, the flux ψ_{md} equals ψ_m, the instantaneous amplitude of air gap flux. In general, this component of flux will be operating in the vicinity of the "knee" of the magnetizing characteristic where saturation becomes important. The magnetizing reactance is effectively the transient saturated reactance ψ_{mt}(sat), the slope of the tangent of the magnetizing characteristic at the operating point. It can be imagined that the operating point continuously moves along the saturated region of the magnetizing characteristic during the dynamic process. The corresponding tangent at the operating point continusously changes its slope as well. An infinity of tangents will constitute the magnetizing characteristic. Therefore, it is simply necessary to incorporate the nonlinear magnetizing characteristic itself into the d axis portion of the d,q model.

Figure 8 is a re-drawn magnetizing characteristic for the purposes of computer simulation. Note that the abscissa of Fig. 2 has been multiplied by the unsaturated d-axis reactace x_m such that $\psi_{md}(\text{unsat}) = i_{md}\, x_m(\text{unsat})$. The ordinate is

$$\psi_{md}(\text{sat}) = \psi_{md}(\text{unsat}) - \Delta\psi_{md} \tag{8}$$

The expressions relating the d axis flux linkage components in the conventional linearized model must be modified as follows:

$$\begin{aligned}\psi_{ds} &= x_{\ell s} i_{ds} + \psi_{md}(\text{sat}) \\ &= x_{\ell s} i_{ds} + \left(\psi_{md}(\text{unsat}) - \Delta\psi_{md}\right)\end{aligned} \tag{9}$$

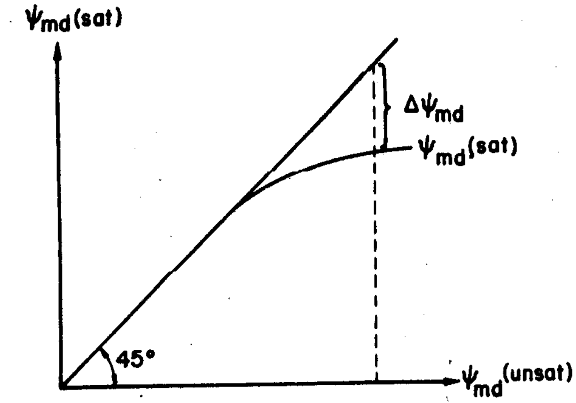

Fig. 8 Re-drawn Magnetizing Characteristic for the Purposes of Computer Simulation.

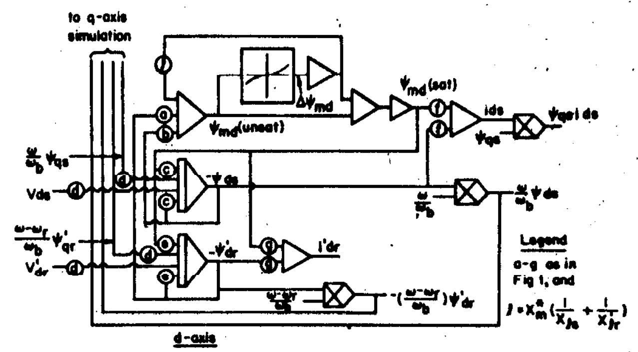

Fig. 9 Simulation Diagram of the Modified d Axis Circuit Including the Effect of Spatially Dependent Saturation.

$$\psi'_{dr} = x'_{\ell r} i'_{dr} + \psi_{md}(sat)$$

$$= x'_{\ell r} i'_{dr} + \left(\psi_{md}(unsat) - \Delta\psi_{md}\right) \qquad (10)$$

$$i_{ds} = \frac{\psi_{ds} - \psi_{md}(unsat) + \Delta\psi_{md}}{x_{\ell s}} \qquad (11)$$

$$i'_{dr} = \frac{\psi'_{dr} - \psi_{md}(unsat) + \Delta\psi_{md}}{x'_{\ell r}} \qquad (12)$$

$$\psi_{md}(unsat) = x_m(unsat)\; i_m$$

$$= x_m(unsat)\,\left(i_{ds} + i'_{dr}\right)$$

$$= x_m(unsat)\,\left[\frac{\psi_{ds} - \psi_{md}(unsat) + \Delta\psi_{md}}{x_{\ell s}} + \frac{\psi'_{dr} - \psi_{md}(unsat) + \Delta\psi_{md}}{x'_{\ell r}}\right] \qquad (13)$$

or

$$\psi_{md}(unsat) = \frac{x_m^*}{x_{\ell s}}\,\psi_{ds} + \frac{x_m^*}{x'_{\ell r}}\,\psi'_{dr} + x_m^*\left(\frac{1}{x_{\ell s}} + \frac{1}{x'_{\ell r}}\right)\Delta\psi_{md} \qquad (14)$$

where

$$x_m^* = \frac{1}{\frac{1}{x_m(unsat)} + \frac{1}{x_{\ell s}} + \frac{1}{x'_{\ell r}}} \qquad (15)$$

Equation 14 illustrates that the unsaturated value of magnetizing reactance is also used in the d axis circuit of the saturated model, but at the same time uses a non-linear relationship $\Delta\psi_{md}$ which concerns how the magnetizing flux saturation is incorporated into this part of the computer model. The quantity $\Delta\psi'_{md} = f(\psi_{md}(unsat))$ is a non-linear function of unsaturated d axis flux and can be simulated with a non-linear function generator in either analog or digital fashion.

Figure 9 shows a simulation diagram of the modified d axis circuit which incorporates Eqs. 9 to 14. Note that the non-linearity associated with the saturation effect has been isolated to a single function generator and that all multiplication or division by non-linear parameters is avoided. In addition it is perhaps important to mention that only integration is used in the simulation and that differentiation of the inductance terms in the flux linkage equations, Eqs. 1-4 is completely avoided. This is in direct contrast to European authors who appear to indicate that such differentiation is necessary for proper simulation of spatially dependent saturation.[10,16]

Experimental Verification of Saturation Model

In many cases the improvement afforded by this new computer simulation may not be of major importance. Such cases are typified by starting behavior in which the air gap flux is typically only a fraction of its rated value. Perhaps the most important influence of the saturation effect is in the damping of electrical transients. In particular, it appears that saturation is particularly important in situations where the machine has nearly zero damping since in this case, the added damping introduced by saturation has a major influence on whether the motor is ultimately stable or unstable. Since small differences in saturation have a noticeable effect on the stability margin, this type of operating condition was chosen to verify the accuracy of the new saturated induction motor model. In particular, the instability region of an induction machine which occurs when a machine is supplied with high source resistance was simulated and compared with measured results.[13]

For this study the machine described in the Appendix was again used. The machine was supplied with a variable sinusoidal voltage by means of an induction regulator. To make the induction machine unstable, additional resistances were added to the three phase stator windings. An experiment was carried out by carefully measuring the terminal voltage and the additional resistance which just causes the machine to produce a sustained oscillation at a particular value of terminal voltage with no-load. The consequent instability region of the machine was plotted as a function of the ratio of total stator resistance (the sum of inherent stator resistance and additional resistance) to rotor resistance $\alpha = \sum r_s/r_r$ as shown in Fig. 10. The line-to-line stator voltage V_{L-L} is used as the ordinate.

The solid line of Fig. 10 shows the measured results. The dot-dashed and the dashed lines show the results of simulation using a conventional saturation model and when the new saturation model with dynamic axes alignment is employed respectively. It can be seen from Fig. 10 that while there are small discrepancies between measurements and computer results using the new model for very high ratios of stator to rotor

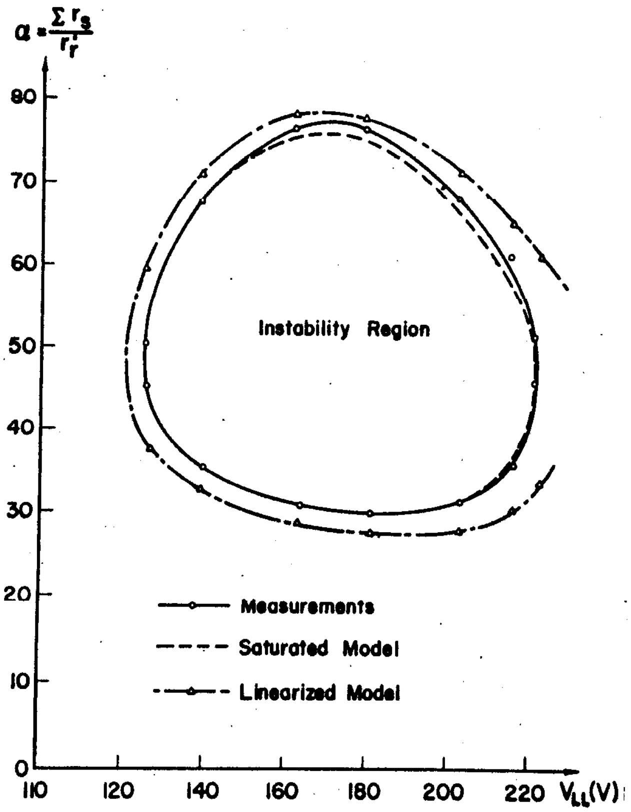

Fig. 10 Instability Region of 7.5 HP Induction Machine with Resistance Inserted in Series with the Stator Phases.

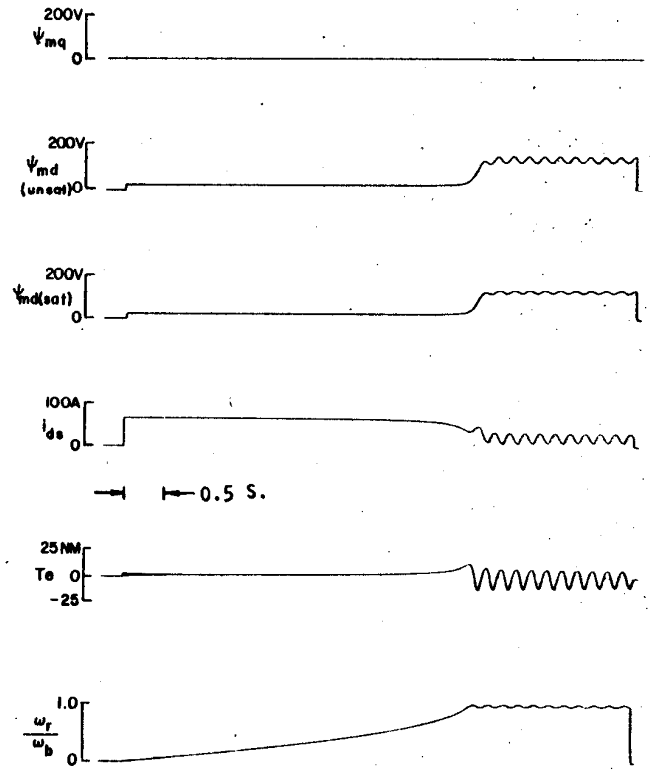

Fig. 11 Analog Computer Traces Illustrating Sustained Oscillation for the Operating Condition, $\sum r_s$ = 3.86 Ω, V_{L-L} = 204 V.

resistance the results are within normal measurement error. The saturated model clearly possesses the capability of predicting dynamic behavior of machine with great accuracy.

Figure 11 displays a set of analog computer traces which illustrates the sustained oscillation introduced by the addition of the external resistances. The traces of saturated and unsaturated magnetizing flux-ψ_{md}(sat) and ψ_{md}(unsat) verify that the relationship between their instantaneous values corresponds exactly to the nonlinear magnetizing characteristic of the machine.

Conclusion

The saturation of the main flux magnetizing field plays an important role in transient as well as dynamic behavior of an induction machine. This paper has demonstrated how the conventional d,q model can be modified to incorporate spatially dependent main flux saturation. Experiments reveal that this new induction motor saturation model can be used to predict dynamic behavior of induction machine with good accuracy. It is clear that this implementation can be readily extended to synchronous machine or other electrical machine models. The approach is equally valid for digital as well as analog computer simulation.

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Appendix

Nameplate Data and Parameters of Test Machine and Voltage Regulator

Nameplate Data: Baldor Electric Co.

Frame 924M 284T	7.5 HP
208/220/440 Volts	21/20/10 Amps
1725 RPM	60 HZ.
3 Phase	1.15 SF 55°C

Parameters:

$r_s = 0.193\ (\Omega)$ $x_{\ell s} = 0.832\ (\Omega)$

$r'_r = 0.123\ (\Omega)$ $x'_{\ell r} = 0.832\ (\Omega)$

$x_m(\text{unsat}) = 16.25\ (\Omega)$

$J = 0.041\ \text{Kg-m}^2$

Voltage Regulator:

$r_\ell = 0.05\ (\Omega)$

$x_\ell = 0.4 \sim 0.1\ (\Omega)$ (function of regulator position)

Discussion

J. E. Brown and **P. Vas**, (Newcastle upon Tyne, England): The problem of the effects of saturation in induction motors is currently receiving considerable attention and the paper is to be welcomed as a further contribution to one aspect of the subject. We identify two key elements in the simulation technique, namely the use of the flux-linkages as state variables and the use of a reference frame in which the d-axis of the reference frame is aligned with the magnetizing flux space vector; and we quote from the paper, "it is perhaps important to mention that only integration is used in the simulation and that *differentiation of the inductance terms* in the flux-linkage equations is completely avoided. This is in direct contrast to European authors who appear to indicate that such differentiation is necessary for proper simulation of spatially dependent saturation." We feel that this, the only reference to our paper [A], might be misleading.

We would point out that we have never suggested anywhere that differentiation of the *inductance terms* in the flux-linkage equations is necessary for proper simulation or computation. We recognize that there are basically two methods of computing the transient performance of a.c. machines; either the currents or the flux linkages can be taken as state variables. *When the currents are chosen differentiation of inductance with respect to magnetizing current arises,* and when flux linkages are chosen it does not. In [A] we use the currents and say "it must be emphasized that in the present paper the currents have been *deliberately* chosen as the state variables in order that the intersaturation effect could be explained both physically and mathematically." We showed that all sixteen terms of the conventional impedance matrix had to be modified. In a later paper [B], which would have not come to the attention of the authors when preparing their paper, we give not only a set of equations with currents as state variables different from those in [A], which have some advantages, but equations with flux linkages as state variables followed by the statement that "the dynamic inductance, L, is not required." In effect the magnetizing inductance $L_m = |\psi_m|/|i_m|$ is required and *differentiation of the inductance terms* in the flux linkage equations does not arise. It is this requirement for only one variable magnetizing inductance, defined by the normal magnetization curve, which is the major advantage arising from the use of flux linkages as state variables in the transient analysis of saturated induction motors.

While we ourselves agree with the authors that advantages arise from the use of flux linkages as state variables there is nevertheless some preference for the use of currents and the consequent $e = Zi$ formulation, as used in generalized machine theory. This is evidenced by excellent recent papers [C,D,E,F]. We have tried in [A] and [B] to make a contribution to the proper formulation of Z. Incidentally, although Z includes both the normal magentizing inductance, L_m, and the dynamic inductance, L, which is the first derivative of the magnetization curve, differentiation doesn't actually arise in computation. The parameters are, of course, treated as known parameters derived from the magnetization curve. What is important, as pointed out in [B], is that in deriving the inductance function L and L_m from this curve by the fitting of successive curves care is taken to ensure that both the fitting curves and their first derivatives match at the beginning and end points of successive intervals.

The special reference frame used by the authors, has been described and logically derived for large signal analysis in [A]. Some of its advantages, particularly the elimination of the cross-saturation effect and some of its disadvantages were discussed. It has been used for large signal analysis in [B] where, utilizing flux linkages as state variables, equations similar to those used by the authors are given, we believe, for the first time, and an application is described. However, it must be admitted, as explained in the oral presentation of [B], that we inadvertently used the word "stationary" instead of "special" for the reference frame. The word "stationary" is only correct if it has the meaning of "stationary with repect to the magnetizing flux vector."

We think it is important to note that the d and q-axis components applicable to Figs. 6 and 7 of the paper under discussion are related to different reference frames. Only those for Fig. 7 are related to the special reference frame. We therefore think it would be helpful if the authors would show how the phase angles between the two reference frames are to be computed.

All the important points raised in this disucssion and many others relevant to the effects of saturation in electrical machines are also discussed in [G] which describes work carried out during the period the authors of the present discussion have been in close cooperation at the University of Newcastle upon Tyne.

REFERENCE

[A] J. E. Brown, K. P. Kovacs, P. Vas, "A method of including the effects of main flux path saturation in the generalized equations of a.c. machines," *IEEE Transactions on PAS,* 1983, vol. PAS-102, no. 1, pp. 96-103. (Ref. 16 of paper under discussion).

[B] J. E. Brown, P. Vas, "The phenomenon of intersaturation in the transient operation of induction motors arising from saturation of the main flux path," IEE International Conference on Electrical Machine-Design and Application, July 13-15, 1982, Conference publication 213, pp. 182-184.

[C] F. A. Fouad, T. W. Nehl, N. A. Demerdash, "Saturated transformer inductances determined by energy perturbation techniques," *IEEE Transactions on PAS,* vol. PAS-101, no. 11, pp. 4183-4193, 1982.

[D] T. W. Nehl, F. A. Fouad, N. A. Demerdash, "Determination of saturated values of rotating machinery incremental and apparent inductances by an energy perturbation method," *IEEE Transactions on PAS,* vol. PAS-101, no. 12, pp. 4441-4451, 1982.

[E] J. A. A. Melkebeek, "Magnetizing-field saturation and dynamic behavior of inducting machines Part 1: Improved calculation method for induction-machine dynamics," *IEE Proc.*, vol. 130, Pt. B, no. 1, pp. 1-9, 1983.

[F] J. A. A. Melkebeek, "Magnetizing-field saturation and dynamic behavior of induction machines Part 2: Stability limits of a voltage-fed induction motor and of a selfexcited induction generator," *IEE Proc.*, vol. 130, Pt. , no. 1, pp. 10-17, 1983.

[G] P. Vas, "Extension of the unified theory of electrical machines, applications of the theory," D.Sc. Thesis, Hungarian Academy of Sciences, Budapest, 1982.

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Y. K. He and T. A. Lipo: The authors welcome the interest shown in their paper by Dr. Brown and Dr. Vas. They comment regarding 1) the use of flux linkages for state variables and 2) the need for differentiation in their simulation. In regard to the point concerning the use of flux linkages it should be pointed out that our comment concerns the use of currents in Refs. 10 and 16 of our paper. The discussers point to a much newer paper (Ref. B) that uses flux linkages as variables. This paper is a conference paper published in England shortly before the Sept. 1 IEEE deadline. We were not aware of this paper until we received our copy of the conference proceedings in April 1983, long after our paper was submitted and presented. The paper does indeed mention, at least briefly, the use of flux linkages as variables. However, no information is provided concerning how these equations may be efficiently solved nor is there any attempt to correlate this model with test results.

The discussers argue that differentiation is not required in their simulation. The point that we make regarding differentiation refers to Ref. 16/A which the discussers readily admit employs differentiation although it is computed prior to commencing the simulation. In both Refs. A and B the solution for the speed of the reference frame must be obtained by differentiating the angular position of the flux vector. We do not see much difference. It appears that differentiation is still used. If it is not, the authors provide no information concerning how it can be avoided.

The discussers ask for the expressions for trnasformed voltages when using a reference frame fixed on the flux vector. The equations which describe the transformation from phase variables to any arbitrary d-q axes (including this one) are given in Ref. 14.

We regret that space constraints imposed by IEEE prompted us to omit the details of the saturation curve from an earlier draft of the paper. When space became avilable in the final copy we forgot to include it. We are happy to supply these data in the table below.

V_{L-L} (V)	30	59·5	89·75	121	140	160·5	179·6	199·5	221·5	239	246	252
I_M (A)	1·25	2·115	3·05	4·08	4·77	5·39	6·42	7·535	9·425	11·86	14	14·3

MAGNETIZATION CURVE

V_{L-L} (V)	$X_{M(SAT)}$ (Ω)	ΣX_{LS} (Ω)	Saturated Model ΣR_S (Ω)	Linearized Model ΣR_S (Ω)
129	16·25	1·252	5·19—6·86	4·9—7·25
142	16·25	1·232	4·36—8·288	4·168—8·673
165	16·1	1·182	3·868—9·218	3·638—9·508
182	15·43	1·032	3·738—9·118	3·448—9·408
204	14·08	0·982	3·858—8·128	3·478—8·73
217	13·14	0·942	4·518—6·98	3·773—7·93
222	12·73	0·922	5·838—6·288	4·104—

PARAMETERS USED FOR FIGURES 6, 7, AND 10

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