GLOBAL JOURNAL OF ENGINEERING RESEARCH VOL. 3, No. 1 & 2, 2004: 71 - 81
 ISSN 1596-292X

DYNAMIC MODELLING AND SIMULATION OF SYNCHRONOUS GENERATOR FOR WIND ENERGY GENERATION USING MATLAB.

O. I. OKORO

(Received 5 April 2004; Revision Accepted 23 June 2004)

ABSTRACT

This paper shows that it is possible to use currently available commercial software to model and simulate the dynamic behaviour of a synchronous Generator for wind energy generation. The resulting system of ordinary differential equations governing both the electrical and mechanical transients of the generator are solved numerically using the in-built Fourth-order Runge-Kutta method in the MATLAB® ODE suite. The computed transient –response results using this method are not only accurate but also computationally economical compare to the solutions obtained by numerical integration on digital computers via writing of programme. The developed model is used to calculate the starting performance of the generator during load variations.

KEYWORDS: Synchronous generator, Wind Energy, Transient response, Modelling, Simulation.

INTRODUCTION

In a developing economy, electrical energy demand is usually on the high side. Obviously, a modern electric power system should be planned to provide electric power at each system bus with a high degree of reliability. This implies that, power system planning must consider not only the dynamic stability of the system but also the dynamic behaviour of the generator that forms the component part of the system for improved future performance (Burchett 1977). One of the basic properties of wind energy generation is load variation. Load variation in wind energy plants usually leads to large inrush transient currents flowing into or out of the machine during starting conditions. These high inrush currents lead to the heating of the machine windings and subsequent loss of winding insulation. Most industrial synchronous generators are usually protected from these inrush currents in order to prevent the machine from continuously starting beyond specified limits(Ojo and Lipo 1989). This makes the study of the transient behaviour of synchronous machine imperative as the knowledge of these inrush currents will assist in overall machine protection and monitoring. Various mathematical models have been developed to describe the transient behaviour of a synchronous machine (Harley, Limebeer and Chirricozzi 1980, Shackshaft 1963, Humpage and Saha 1967). The models differ in degree of complexity and accuracy and are computed by numerical integration on digital computers. This paper shows that it is possible to use a commercially available software package, MATLAB® to model and simulate the dynamic behaviour of a synchronous generator for wind energy generation. The proposed method is not only efficient but also computationally economical as the time used in writing user's programme for inversion, integration and graph plotting is averted. The paper presents the d-q modelling of the electrical model of the generator. The mechanical model is developed together with the computer simulation and results. Finally, the results are discussed with relevant conclusion.

ELECTRICAL MODEL OF GENERATOR

In the development of the electrical model, the following simplifying assumptions are made (Adkins 1951):
Negligible magnetic saturation and eddy current effects.
Windings produce a sinusoidal distribution of mmf and flux density.
The magnetic circuits are assumed to be symmetrical.
Park's equations for a synchronous generator equipped with two sets of damper windings and one field winding are as follows (Park 1929):

O. I. OKORO, Department of Electrical Engineering, University of Nigeria, Nsukka, Enugu State - Nigeria

- **Armature Equations**

$$V_d = -R_s i_d - \omega_r \lambda_q - L_d \frac{di_d}{dt} + L_{md} \frac{di_{fd}}{dt} + L_{md} \frac{di_{kd}}{dt} \quad (1)$$

$$V_q = -R_s i_q + \omega_r \lambda_d - L_q \frac{di_q}{dt} + L_{mq} \frac{di_{kq}}{dt} \quad (2)$$

Where,

$$\lambda_d = -L_d i_d + L_{md}\left(i_{fd} + i_{kd}\right) \quad (3)$$

$$\lambda_q = -L_q i_q + L_{mq} i_{kq} \quad (4)$$

$$L_d = L_{ls} + L_{md} \quad (5)$$

$$L_q = L_{ls} + L_{mq} \quad (6)$$

- **Field Equation**

$$V_{fd} = R_{fd} i_{fd} - L_{md} \frac{di_d}{dt} + L_f \frac{di_{fd}}{dt} + L_{md} \frac{di_{kd}}{dt} \quad (7)$$

where,

$$L_f = L_{lfd} + L_{md} \quad (8)$$

- **Damper winding Equations**

$$V_{kd} = 0 = R_{kd} i_{kd} - L_{md} \frac{di_d}{dt} + L_{md} \frac{di_{fd}}{dt} + L_{kd} \frac{di_{kd}}{dt} \quad (9)$$

$$V_{kq} = 0 = R_{kq} i_{kq} - L_{mq} \frac{di_q}{dt} + L_{kq} \frac{di_{kq}}{dt} \quad (10)$$

Where,

$$L_{kd} = L_{lkd} + L_{md} \quad (11)$$

$$L_{kq} = L_{lkq} + L_{mq} \quad (12)$$

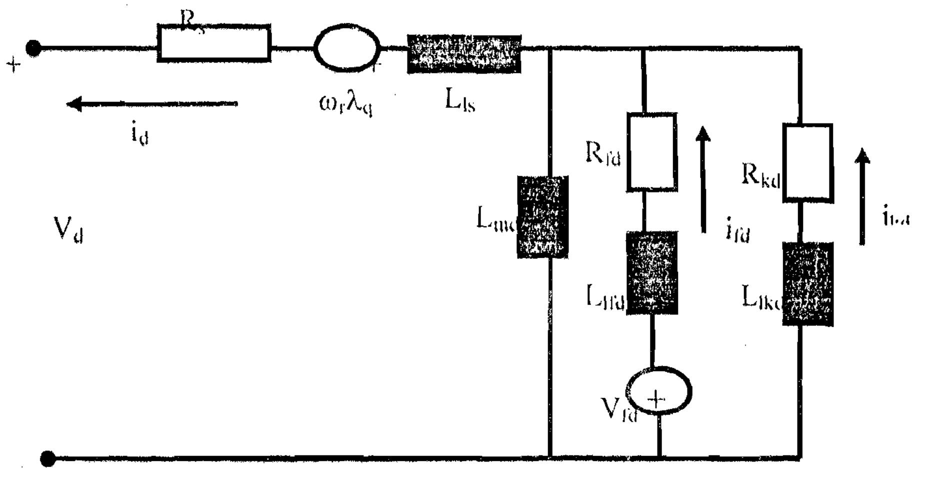
In the above equations, the following parameters and variables are defined as follow;
ω_r =rotor speed, V_d=armature d-axis terminal voltage, V_q=armature q-axis terminal voltage, i_d=armature d-axis terminal current, i_q=armature q-axis terminal current, V_{fd}=field winding terminal voltage, i_{fd}=field winding terminal current, i_{kd}=d-axis damper winding current, i_{kq}=q-axis damper winding current, λ_d=total armature flux in d-axis, λ_q=total armature flux in q-axis, R_s=armature phase resistance, L_{ls}=armature phase leakage inductance, L_{md}=d-axis coupling inductance, R_{fd}=field winding resistance, L_{lfd}=field winding leakage inductance, R_{kd}=d-axis damper winding resistance, L_{lkd}=d-axis damper winding leakage inductance, L_{mq}=q-axis coupling inductance, R_{kq}=q-axis damper winding resistance, L_{lkq}=q-axis damper winding leakage inductance

Equations (1)-(12) describe the synchronous generator's equivalent circuit in the rotor reference frame shown in Figure 1.

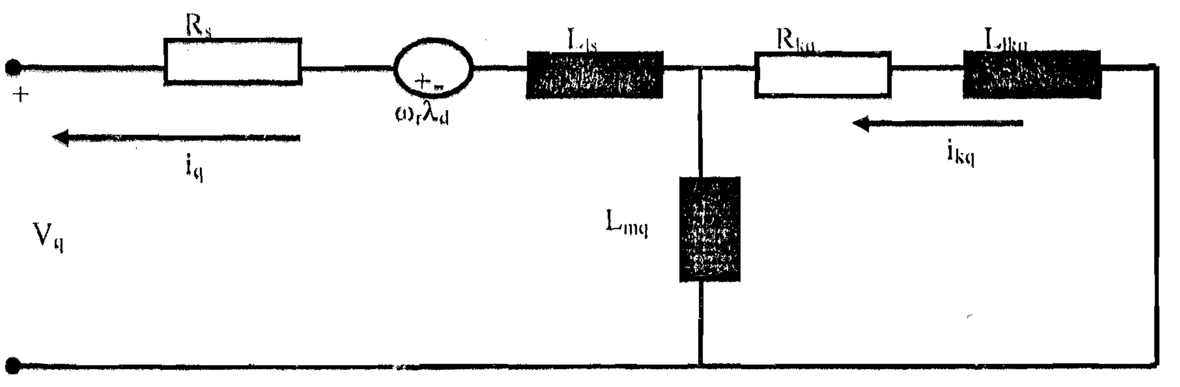
For the purpose of this investigation, the voltage equations can be represented in state variable form with currents as state variables (Adkins and Harley 1975).

$$p[\mathrm{i}] = [\mathrm{L}]^{-1}\left([\mathrm{u}] - \left([\mathrm{R}] + \omega_r + [\mathrm{G}]\right)[\mathrm{i}]\right) \quad (13)$$

Where,



(a) Direct axis



(a) Quadrature axis

Figure 1. Synchronous generator equivalent circuits in rotor reference frame.

$$[\mathbf{R}] = \begin{bmatrix} -R_s & 0 & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 & 0 \\ 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{bmatrix} \quad (14)$$

$$[\mathbf{i}] = \begin{bmatrix} i_d & i_q & i_{fd} & i_{kd} & i_{kq} \end{bmatrix}^T \quad (15)$$

$$[\mathbf{u}'] = \begin{bmatrix} u_d & u_q & u_f & 0 & 0 \end{bmatrix}^T \quad (16)$$

$$[\mathbf{L}] = \begin{bmatrix} -L_d & 0 & L_{md} & L_{md} & 0 \\ 0 & -L_q & 0 & 0 & L_{mq} \\ -L_{md} & 0 & L_f & L_{md} & 0 \\ -L_{md} & 0 & L_{md} & L_{kd} & 0 \\ 0 & -L_{mq} & 0 & 0 & L_{kq} \end{bmatrix} \quad (17)$$

$$[G] = \begin{bmatrix} 0 & L_q & 0 & 0 & -L_{mq} \\ -L_d & 0 & L_{md} & L_{md} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (18)$$

The phase voltages may be considered as sinusoidal and expressed as

$$V_{as} = V_p \cos \omega_b t \quad (19)$$

$$V_{bs} = V_p \cos\left(\omega_b t - \frac{2\pi}{3}\right) \quad (20)$$

$$V_{cs} = V_p \cos\left(\omega_b t + \frac{2\pi}{3}\right) \quad (21)$$

These voltages are related to the d-q frame of reference by (Krause and Thomas 1965).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = [C]\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (22)$$

Where,

$$[C] = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (23)$$

On simplification of equation(22), we have

$$V_d = V_p \sin(\theta - \omega_b t) \quad (24)$$

$$V_q = V_p \cos(\theta - \omega_b t) \quad (25)$$

But,

$$\delta = \theta - \omega_b t \quad (26)$$

Where,

δ = rotor angle with reference to infinite bus, ω_b = synchronous speed, V_p = peak value of infinite bus voltage.

The electromagnetic torque is given by

$$T_e = [i]^T [G][i] \quad (27)$$

The power, P_e at the generator terminals and the total stator current, i_m are respectively expressed as,

$$P_e = V_d i_d + V_q i_q \quad (28)$$

$$i_m = \left(i^2_d + i^2_q\right)^{1/2} \quad (29)$$

MECHANICAL MODEL OF GENERATOR

Since the synchronous generator is to be used for wind energy generation, the mechanical model of the generator should consists of three systems(Wind turbine, Gearbox and Generator) as shown in Figure 2. The general equation of the coupled system with damping coefficients can be expressed in matrix form as (Heier 1998):

$$\begin{bmatrix} \dot{\omega}_{rt} \\ \dot{\omega}_{r} \\ \dot{\theta}_{rt} \\ \dot{\theta}_{r} \end{bmatrix} = \begin{bmatrix} -(d_{Ri}+d_{Ri}) & d_{Ri} & -c_w & c_w \\ d_{Ri} & -(d_{R2}+d_{Ri}) & c_w & c_w \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_{rt} \\ \omega_{r} \\ \theta_{rt} \\ \theta_{r} \end{bmatrix} + \begin{bmatrix} \frac{1}{J_{rt}} & 0 & 0 & 0 \\ 0 & \frac{1}{J_G} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_L \\ T_e \\ 0 \\ 0 \end{bmatrix} \quad (30)$$

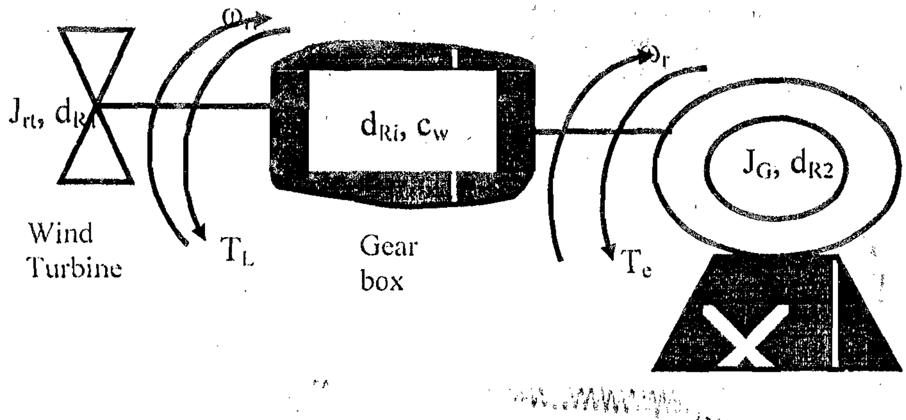


Figure 2. Generator mechanical model schematic with coupling.

Where,

T_L=wind turbine drive torque, T_e = electromagnetic torque, J_{rt} =moment of inertia of wind turbine, J_G = moment of inertia of generator, θ_{rt} = angle of rotation of turbine, θ_r = angle of rotation of generator, ω_{rt} = angular speed of the turbine rotor, ω_r = angular velocity of the generator, c_w = torsion resistance, d_{Ri} = self-damping coefficient of turbine, d_{R2} = self-damping coefficient of generator.

The experimental determination of the system torsion resistance as well as the moment of inertia has been reported by Okoro (Okoro 2002). The values of the damping coefficients were obtained from the manufacturer's data on the test machine.

The load torque is assumed to take the form of a square-wave as shown in Figure 3.

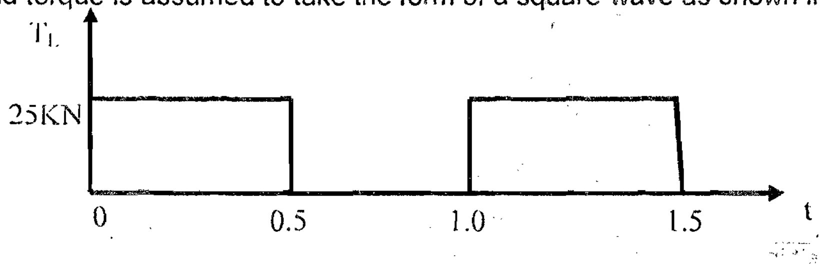


Figure 3: Variation of load torque with time.

EXPERIMENTATION AND COMPUTER SIMULATION RESULTS.

The test machine is a **SCHORCH** VDE 0530, class F insulation, surfaced-cooled synchronous generator. The rated power, speed and current are 10hp, 1500rpm and 58.5A respectively. The test machine is a four-pole generator with 50Hz rated frequency and 250V rated voltage. In order to determine the test machine parameters necessary to carry out the dynamic studies, the conventional methods of no-load and short circuit tests as reported by (Ojo and Lipo 1989) were adopted. The method is less cumbersome and requires little efforts compare to the finite element method of determining the machine parameters as describe by Ojo (Ojo 1987). The mechanical and electrical parameters of the test synchronous generator are given in Table 1.

MATLAB function program which describes the differential equations of the machine model in dynamic conditi[illegible]s developed and solved using the in-built Adams numerical m[illegible]od (The [illegible]ATLAB 19[illegible]7).

Together with the mechanical model of the machine, the dynamic behaviour of the synchronous generator at varying load condition was simulated. Figure 4 shows the graph of mechanical speed against time. The graph shows that the steady state mechanical speed of the generator is attained 0.5s after the transient period. The steady-state period of the electromagnetic torque is distorted due to load variation as shown in Figure 5. The graph of speed against time in Figure 6 shows that the steady-state speed is not affected by load application. The time function of the terminal voltage is shown in Figure 7. Figure 8 shows that the rotor angle rises steadily to its maximum within a shorter time period. It remains constant after 0.5s but increases beyond its steady state value due to load application.

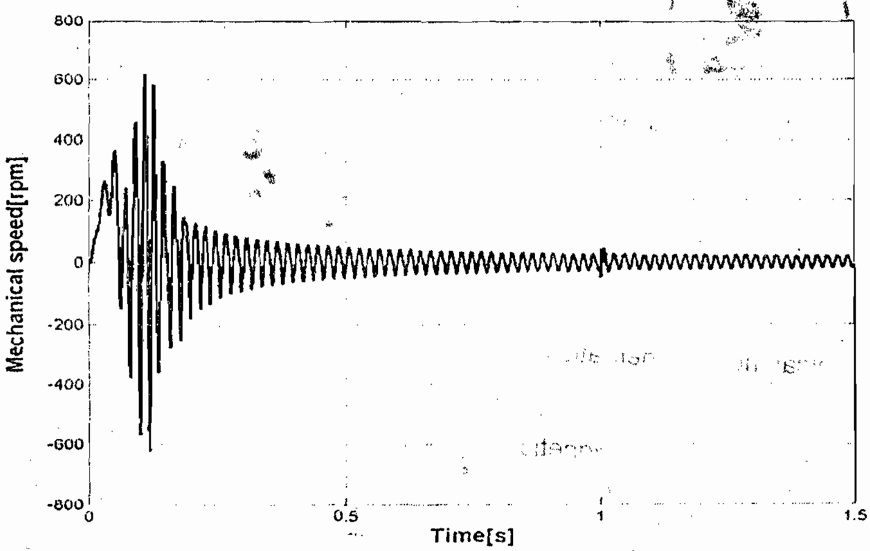


Figure 4. Graph of mechanical speed against time.

Table 1: Test machine parameters.

Frequency, f	50Hz
Rated power, P	10hp
Rated speed, N	1500rpm
Rated current, I	58.5A
Rated voltage, V	250V
Armature phase resistance, R_s	0.137Ω
Field winding resistance, R_f	0.0266Ω
Field winding self inductance, L_f	46.57mH
D-axis damper winding self inductance, L_{kd}	43.364mH
Q-axis damper winding self inductance, L_{kq}	21.147mH
D-axis damper winding resistance, R_{kd}	0.120Ω
Q-axis damper winding resistance, R_{kq}	0.120Ω
Armature phase leakage inductance, L_{ls}	0.897H
D-axis coupling inductance, L_{md}	43.2mH
Q-axis coupling inductance, L_{mq}	20.8mH
Q-axis self inductance, L_q	21.687mH
D-axis self inductance, L_d	44.097mH
Field winding terminal voltage, V_{fd}	125V
Number of pole pairs, P	2
Moment of inertia of wind turbine, J_{rt}	0.6123Kgm^2
Moment of inertia of generator, J_G	1.050Kgm^2
Torsion resistance, c_w	1525Nm/rad
Damping coefficient of gear box, d_{Ri}	52Nm/rad/s
Self-damping coefficient of turbine, d_{R1}	12Nm/rad/s
Self-damping coefficient of generator, d_{R2}	5.0Nm/rad/s

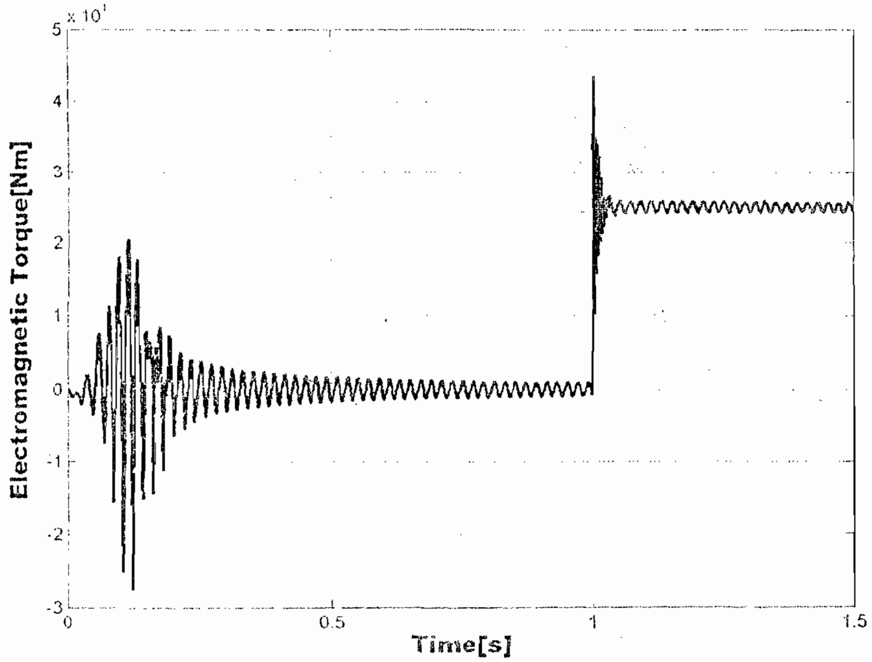


Figure 5: Graph of electromagnetic torque against time.

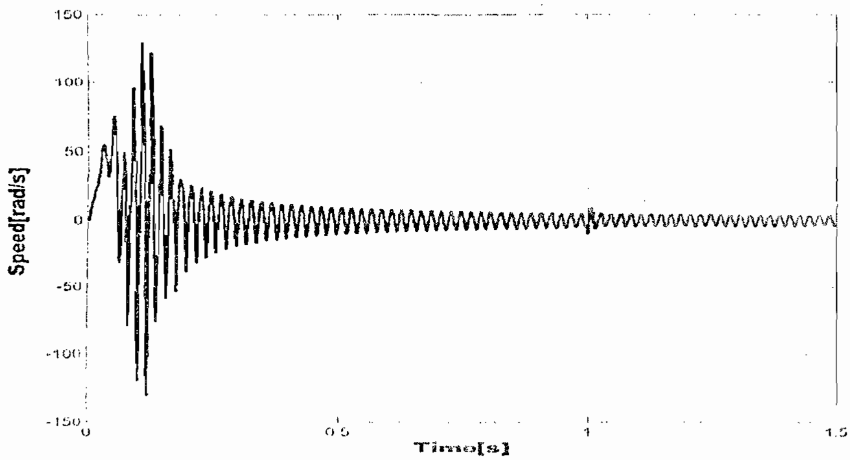


Figure 6: Graph of speed against time.

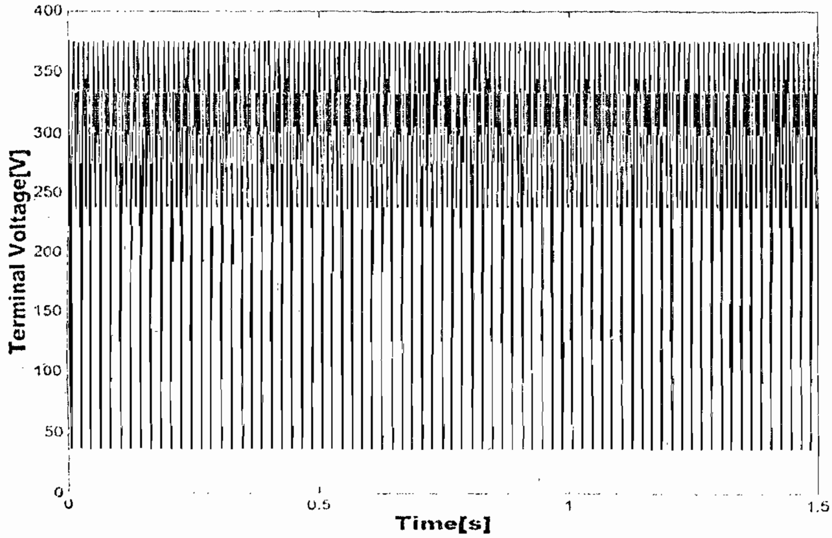


Figure 7. Graph of terminal voltage against time.

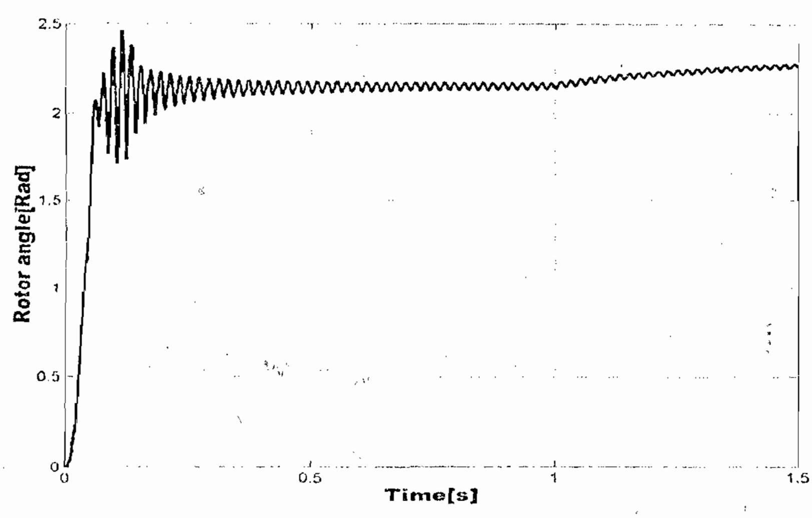


Figure 8. Graph of rotor angle against time.

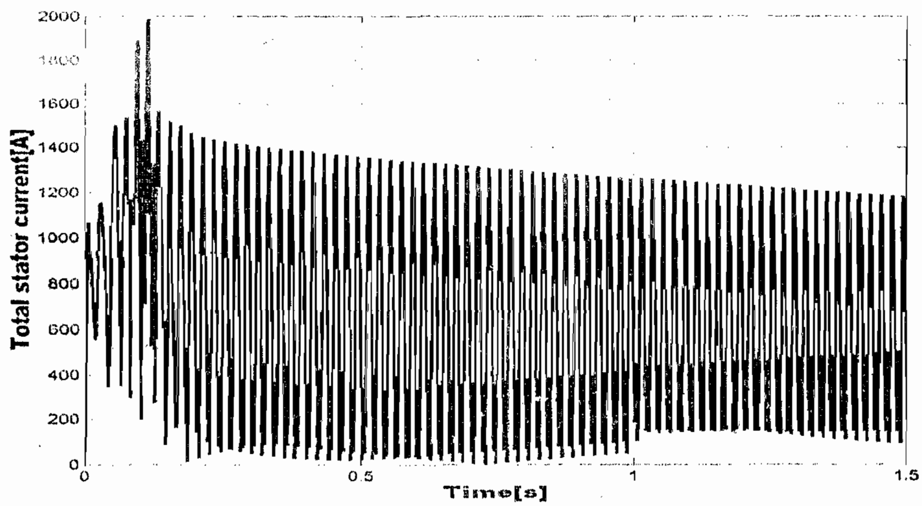


Figure 9: Graph of total stator current against time.

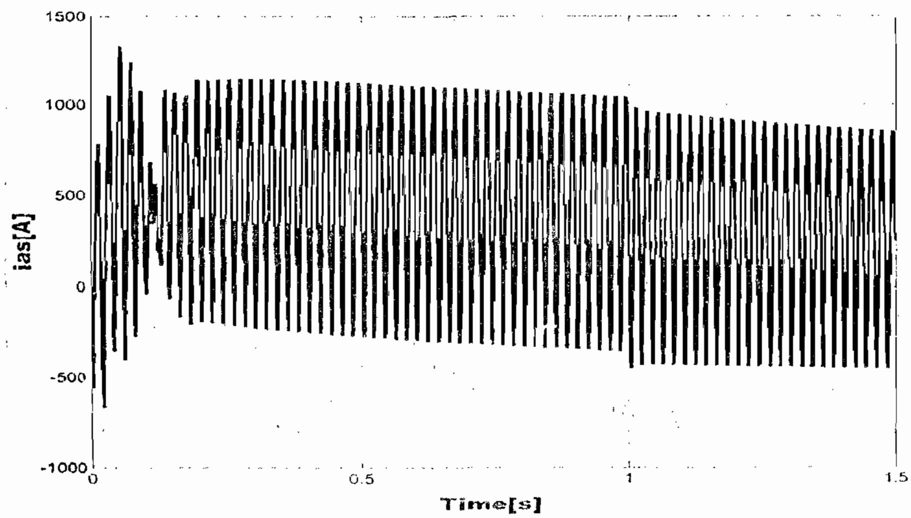


Figure 10. Graph of stator phase current , ias against time.

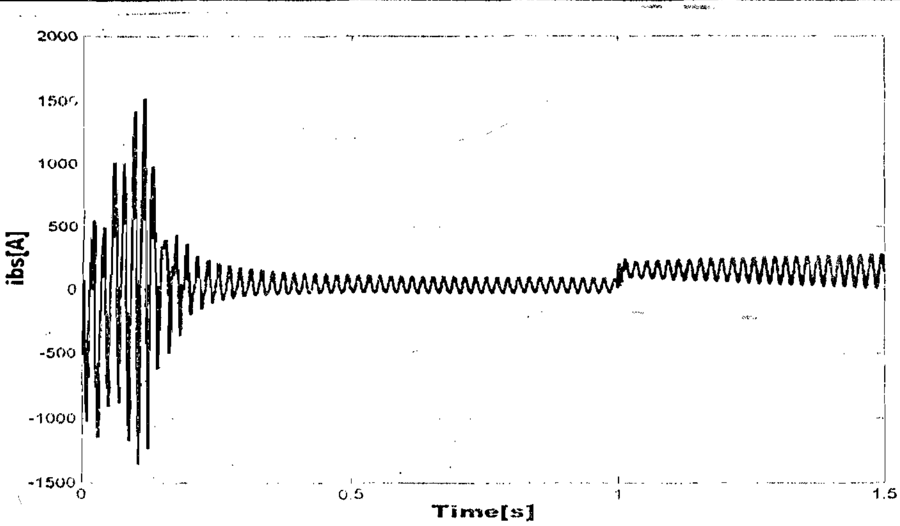


Figure 11. Graph of stator phase current ,ibs against time.

The time function of the total stator current is shown in Figure 9. The initial rise or the total stator current is instructive. This is expected due to high level of flux in the machine during the transient period. The phase currents as a function of time are depicted in Figure 10, Figure 11 and Figure 12.

Figure 11 shows that the generator experienced higher initial magnitude of current in phase b than in other phases. The steady-state value of the phase b current is lower than that of the other phases. This was as a result of the applied voltage and the intermittent load changes which offset the phase currents. The time function of the power at the generator terminals is given in Figure 13.

The Figure shows that at about 0.5s, the power at the generator terminals is zero. There is however, an offset in the power 1s after the load application.

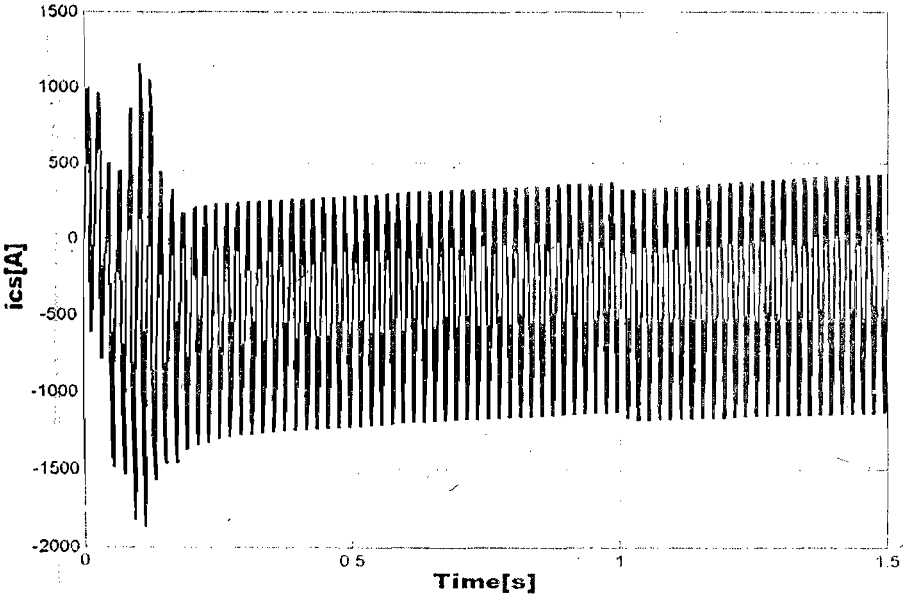


Figure 12. Graph of stator phase current ,ics against time.

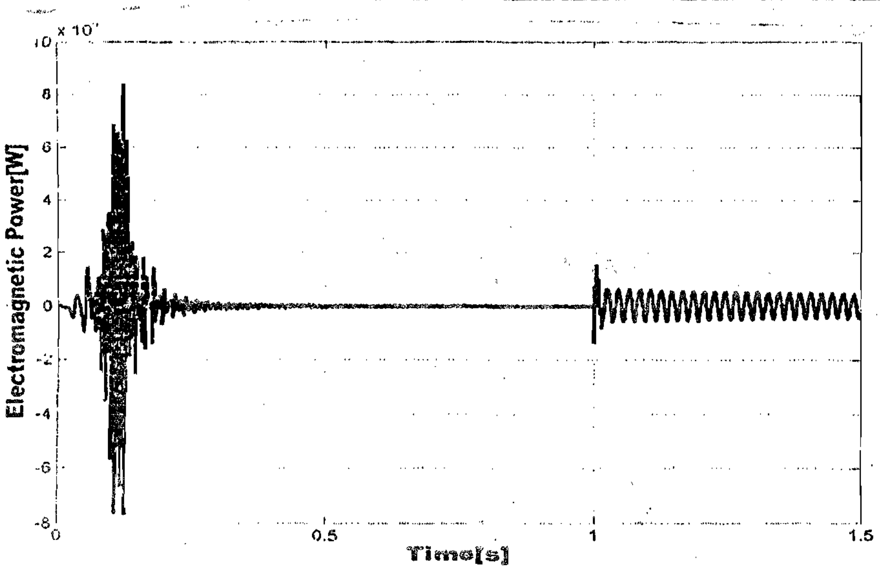


Figure 13. Graph of electromagnetic power against time.

The results presented in this paper compare favourably in trend with earlier works on the subject by the researchers (Ojo and Lipo 1989, Harley, Limebeer and Chirricozzi 1980, Shackshaft 1963, Adkins 1951). However, in contrast, the paper has employed a commercial scientific software, MATLAB® to study the dynamic behaviour of synchronous generator for wind energy generation under varying load conditions. It can be said that while previous researchers on the subject have developed subroutine programs to handle the non-linear differential equations, such efforts have been found to be involving, energy sapping and much prone to error than the efficient and faster MATLAB built-in ODE solvers which the paper has avail itself.

CONCLUSION

This paper has presented a simple method of modelling synchronous generator suited for wind energy generation. The equations for the model have been derived and then expressed as a state equation which can be solved by a standard numerical method. The use of MATLAB program as a simulation aid to demonstrate the dynamic performance of synchronous machine is of academic importance. The representations which have been developed in this paper for synchronous generator enable demonstration of the complete dynamic performance of an important type of electric machine that finds application in wind energy generation. By studying the response curves, the plant Engineer will be better informed about the generator dynamics prior to loadability.

ACKNOWLEDGEMENT

The author would like to thank Prof. Dr.-Ing. B. Weidemann for his useful discussion on the subject and to **DAAD** for her financial assistance during the research work at the University of Kassel, Germany.

REFERENCES

Adkins, B., 1951. Transient theory of synchronous generators connected to power systems. Proc. IEE PP. 510-523.

Adkins, B. and Harley, R.G., 1975. The General theory of alternating current machines: Application to practical problems. Chapman and Hall, London.

Burchett, R. C., 1977. Probabilistic methods in power system dynamic stability studies. Dissertation, Purdue University.

Harley, R. G., Limebeer, D. J. N. and Chirricozzi, E., 1980. Comparative study of saturation methods in synchronous machine models. IEE Proc., 127(1): 1 - 6.

Heier, S., 1998. Grid integration of wind energy conversion systems. John Wiley and Sons, New York.

Humpage, W. D. and Saha, T. N., 1967. Digital-computer methods in dynamic-response analysis of turbo generator units. Proc. IEE , 114: (8): 1115-1130.

Krause, P. C. and Thomas, C. H., 1965. Simulation of symmetrical induction machinery. Transactions IEEE, PAS-84, 11 : 1038-1053.

Ojo, J. O., 1987. Saturation effects in alternating current electric machines. Ph.D. Thesis, University of Wisconsin-Madison.

Ojo, J. O. and Lipo, T. A., 1989. An improved model for saturated salient pole synchronous motors. IEEE Transactions on Energy conversion, 4(1): 135-142.

Okoro,O. I., 2002. Dynamic and thermal modelling of induction machine with non-linear effects. Doctor of Engineering thesis, University of Kassel, Germany.

Park, R. H., 1929. Two-reaction theory of synchronous machines, General method of analysis- Part 1, AIEE Transactions, 48: 716 - 727.

Shackshaft, G., 1963. General-purpose turbo-alternator model. Proc.IEE, 110(4): 703-713.

The MATLAB, 1997. The MATLAB Compiler User's guide" , in Mathworks handbook. Math works, Natick.