ELECTRICAL MACHINES AND SYSTEMS: THE CHALLENGE FOR A CULTURE OF SELF-RELIANCE

BY

C. C. OKORO

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IN DEED AND IN TRUTH

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ELECTRICAL MACHINES AND SYSTEMS:

THE CHALLENGE FOR A CULTURE OF SELF-RELIANCE

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by

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ON THE MARBLE

He who adds not to his learning diminishes it.

The Talmoud Tabloid

The man who gets the most satisfactory result is not always the man with the most brilliant single mind but rather the man who can best co-ordinate the brains and talents of his associates.

Alton Jones

The final test of a leader is that he leaves behind him in other men conviction and the will to carry on.

Walter Lippmann

Experience is not what happens to you; it is what you do with what happens to you. Aldous Huxley

The quality of a person's life is in direct proportion to their commitment to excellence, regardless of their chosen field of endeavour.

Vince Lombardi

Education is what survives when what has been learnt has been forgotten. B.F. Skinner

Man's mind once stretched by a new idea, never regains its original dimension. Oliver Holmes

It is necessary that Nigerian Society of Engineers be engaged constantly in Community Engineering in one or several disciplines of relevance to our different locations in addition to the complex, prestigious and expensive projects.

Engr. V.I Maduka, Past President, NSE

Men are wise in proportion not to their experience, but their capacity for experience. George Benard Shaw

You can't get experience by doing nothing. Most people can hardly talk about what they are doing. Anonymous

A statement about a quantity, which can never be tested, is meaningless in engineering, although it may form the basis of meaningful mathematics. Hammond .P.

Teaching should be such that what is offered is perceived as a valuable gift and not as a hard duty.

If we know what it was we were doing it would not be called research, would it?

Before God we are all equally wise and equally foolish.

Albert Ernestine 1879-1955

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1. PROLOGUE

I am indeed very delighted to deliver this lecture. In the parlance of an inaugural lecture being a debt owed the University, I believe that a single lecture is not enough for me to pay the debt I owe the University of Lagos. I was privileged to return to the University as a Graduate Assistant after graduation. I was also privileged to do a Doctoral research on study leave from the University. I benefited in many other ways that I have had to pledge to serve this University with all my strength.

"I pledge to Unilag, my Alma-mater
To be faithful, loyal and honest
To contribute to her Development with all my strength
To uphold her Honour and Glory
So help me God"

I wish to start this lecture with a discourse on materials and associated fundamental forces, which are basic to all fields of engineering. This is because Nigeria is blessed with natural and synthetic (petroleum based) raw materials and there are likely to be increased effort in future to develop industrial materials from local raw materials. It is also interesting to consider some common features in all matter and indeed all creation and the expansive territory of knowledge that had to be conquered before man understood the nature of electricity.

Nature has provided a range of fundamental forces which the early man had to appreciate: the natural electric force, gravitational or earth's magnetic force, coulomb's force and frictional force. Attempts to understand and harness these forces led to the birth of modern science, engineering and technology. Electricity and magnetism were soon found to be inter-related and can be transformed into each other.

Material scientists and Astrologers found common grounds in the structure of the atom and the solar system. It is the gravitational force that makes the moon move round the earth day after day. All bodies consist of charged atoms, which obey the inverse square law of coulomb's force, and the atom in its structure can be said to be a miniature solar system. Just as an atom is a miniature solar system, the constellation of the solar system is often described as a big atom. It becomes clear that life was held together through the activities of rotation and balance of forces. At the centre of the earth the gravitational force reaches its maximum strength and ensures that the earths crust does not disintegrate. The rotating electrical machine is a product of an attempt to harness the reaction between electric and magnetic fields to do useful work. A number of forces in a rotating electrical machine are carefully controlled or suppressed to enable one harness the energy of rotation.

Extensive application of electricity in today's modern industrial society could not have been possible without the benefit of certain types of materials. The ability of some materials to conduct electricity freely, slowly in others or with extreme difficulty in yet other types of materials classify materials into conductors, semi-conductors and insulators. Magnetic and non-magnetic materials are also vital for the electromagnetic and other structures of electrical machines.

Application of materials depends on their atomic structure or position in the periodic table. All matter is made of aggregates of atoms, which have similar structures. On the one hand, Scientists have completed the first phase of smashing the atom and released powerful large amount of energies, which express themselves in the atomic bomb. Today about thirty percent of the worlds electricity needs are generated from nuclear fission and fusion of the atoms of some materials.

Some astrologers have said that the atom is a little living being and if the solar system is a giant atom then there must be a giant living being imprisoned in the Solar system. On the other hand, it stands to reason to argue that all matter were created by this giant being, the Almighty God, in whom we have our beginning, in whom we have our end and in whom we have our being. Recently, Oyibo G {1,22} proposed the God Almighty Grand Unified theorem (GAGUT), the theory of everything, on the forces of nature. Whilst Newton explained how the planets move through the Universal gravitational law, GAGUT investigates the dynamics of how God created the Universe. Many scientists regard this theory as solution to the long known mathematical question on the origin of the Universe.

Leaving the precincts of the atom we step into the realm of molecules. All matter, from the inanimate to the living are molecular in nature. Gases consist of molecules moving in a void. Liquids are molecules whose space have been so reduced that they press against one another and roll against each other like the elements in a ball bearing. Below a certain temperature the molecules no longer change their positions but vibrate and rotate around a fixed point becoming solids. These three states of matter, solids, liquids and gases, are important in a range of electrical engineering materials known as insulators. Our understanding of their performance in service depends a great deal on our understanding of their inner atomic and molecular forms.

The physical quantity distinguishing the ability of a given material to conduct electricity is its resistivity. This property is used to distinguish between conductors, semi-conductors and insulators. Under the action of an electric field or potential difference, electric charges in a conductor move in a direction and constitute electric current.

Once the mystery of currents in conductors was understood, it was then possible to show that magnetism is associated with flow of current on the one hand and that the movement of magnets produced currents in nearby coils on the other. Thus electricity and magnetism were different but related phenomena and magnetism can be converted to electricity.

Maxwell's contributions produced what may be called generalized equations for modern electrical engineering with applications in both light and heavy current. It is interesting that manipulation of Maxwell's equations leads to the celebrated diffusion equation of Poisson, which has applications in most fields of engineering and once again implying a common motive force and origin for all matter.

2. INTRODUCTION

The inquisitive nature of man led to observations of natural and static electricity. Magnetic effects were observed in lodestones and electrical effects thought to be present in lighting. Static electricity was also observed when materials such as natural resins and amber were rubbed together. Many scientists made recognized contributions in the discovery and development of electricity and electrical machines in particular.

Alessandro Volta in 1780 invented the voltaic cell from a chance observation of his fellow Frenchman Lungi Galvanic, an anatomist that the legs of a dissected frog twitched when touched with certain metals. Volta concluded that electricity was produced when the dissimilar metals touched the leg simultaneously and that the electricity came from the metals. Thus he invented the voltaic pile, the predecessor of the battery, the initial source of steady electricity. Various efforts to understand the steady current and its electromagnetic properties became the basis of a new discipline of electrical engineering in the early 19th century. Applications of electricity were mainly in electro-chemistry, the carbon arc and the electric telegraph. At this time electricity and magnetism were thought to be separate and unrelated phenomena.

J.C Oersted in 1820 showed that the flow of electricity produces magnetic fields and the phenomena were interrelated. Magnetism had two polarities as had static electricity and the law of inverse squares operated in both phenomena. The contributions of Oersted inspired the Frenchman A.M Ampere to enunciate principles and laws which are today the basis of everyday electrical engineering. Notable amongst these are the forces between parallel conductors carrying current. He also mooted the idea of electromagnetic rotation. It was Michael Faraday, an English man, who in 1821 experimentally demonstrated the interrelation between electric and magnetic fields and thus provided the basis for the rotating electric motor. Faraday's further experimentation led to the law of electromagnetic induction in 1831. He provided another means of producing electricity by converting magnetism into electricity. This law influenced the development of the transformer, the alternator, the induction machine and thus led to rapid development of electric power engineering. Transmission of power over long distances became possible and the induction machine became widely applied in industry. Public supply of electricity became feasible through national grid power networks. Electric Railway traction became rapidly adopted in the search for improved standards of living for European Societies.

Electrical Machines have given to mankind the spirit of efficiency. Efficiency in ensuring that the losses are minimized in the energy conversion process. Efficiency in ensuring that materials are used to the best advantage. Electrical Machines have taken the burden off labour by becoming the workhorse of large and medium scale industries. They generate all the electricity to drive the economy. They are indeed the items of equipment that we need to automate a number of production processes in our search for a new culture of self-reliance.

In this lecture, some insight is given into the design, construction, modeling and analysis of electrical machines using prototypes and teaching modules at the University of Lagos. Prototypes of power semi-conductor controllers for electrical machines developed as laboratory equipment are used to illustrate modern electronic controls in the power industry. The University laboratory can be shown to hold the key to the development of practical and analytical skills for the effective operation of power utilities and industrial production facilities.

Research efforts in a University laboratory can impact Society {2}. Engineering and Technology development have over the years, been achieved by the joint effort of Engineering faculties, Research institutes, corporate and professional bodies that seek to achieve well articulated development plans. In Nigeria these groups have over the years worked independently. The need for clearly defined goals for science and technology development and a more interactive environment that can engender progress in technology acquisition so as to develop the much-needed culture of self reliance [2] is fully discussed.

3. THE ELECTROMAGNETIC MACHINES AND SYSTEMS

A good illustration of the electro-magnetic machine in the service of man is the modern large capacity generating plant shown in fig 1. It shows a typical power station electro-magnetic machine and the many peripheral equipment associated with its operation. It contains a large number of variables that must be monitored and controlled in order to achieve specified operation of the systems. The computer displays the magnitude of the variables of the system, takes decisions in its central processing unit as to the state of the system as well as issues instructions as to remedial measures to be taken at any instant. Computers are today increasingly being applied in modern power systems instrumentation and control.

The electro-magnetic machine of fig 1 converts the mechanical energy from the turbine to electrical energy. Such machines can in other applications operate as motors, converting electrical energy to mechanical energy. Not all electromagnetic machines are designed to provide continuous rotary motion. The linear motor transfers electrical energy to linear mechanical motion. The moving coil measuring instrument is an electric motor whose motion is restrained through part of a revolution. There are reciprocating machines, which move through an angle and return to their previous position. Some other precision control machines change their position in response to current pulses fed from a controller. They are all based on the principle that electric and magnetic fields interact to produce forces.

The power transformer is a static electromagnetic machine whose invention made possible the transmission of power over long distances and its distribution within large conurbations. It is a vital part of the power networks that support the economy and the large appetite for modern living of today's society.

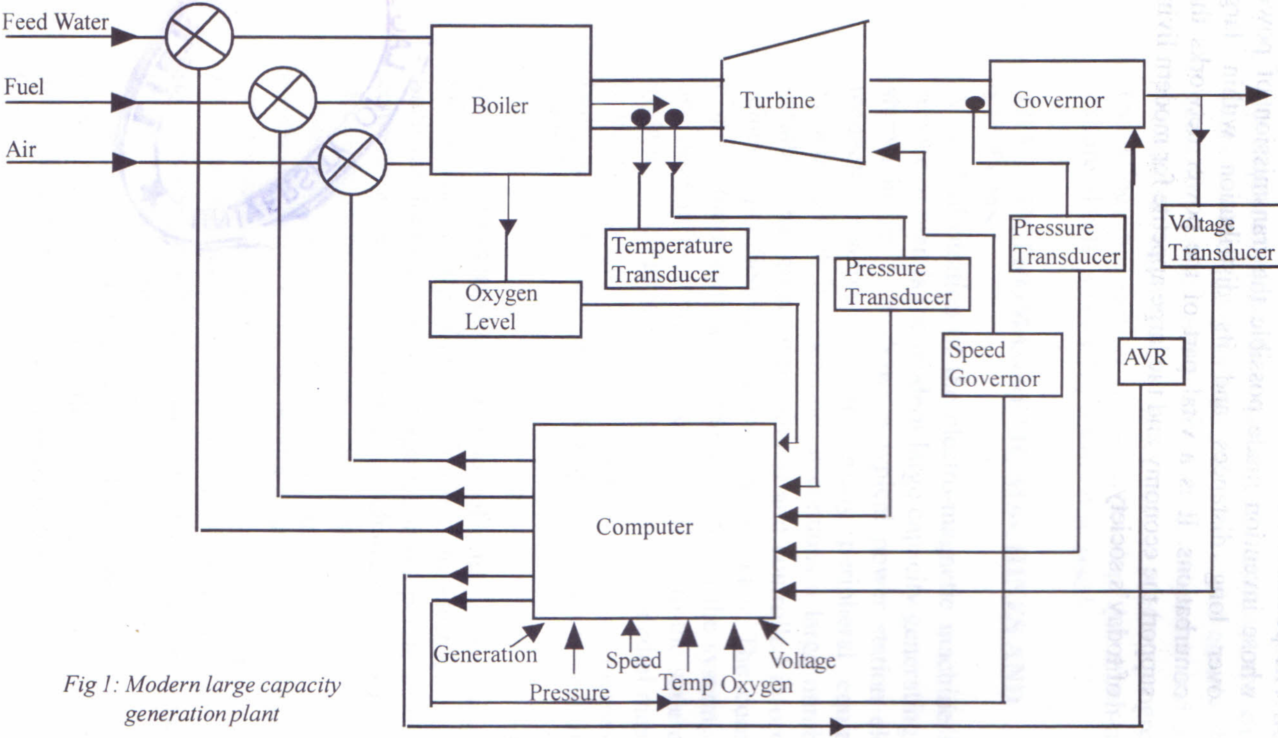


Fig 1: Modern large capacity generation plant

4. ELECTROMAGNETIC MACHINES IN ENERGY GTD

Power systems have today become large networks of generation facility, transmission lines and substation switching and control equipment, which can only be run efficiently using modern financial and management techniques.

Fig 2 illustrates how electrical power is transmitted over long distances in order to get electricity from distant power stations such as Jebba and Shiroro to large conurbations such as Lagos. Electric power is transmitted at high voltage (330kv) because of inherent advantages in transmission at high voltages. Transmission of electric power over long distances has led to the National Grid Network, which interconnects all the power stations in the country. With such a system, power stations are built at the most advantageous sites where the energy requirement is readily available. The newer and more efficient stations may be loaded continuously whilst the less efficient and older stations are used for peak periods and for reactive power control. Also, voltage and frequency at various points of the network can be standardized.

It is of historical interest to consider the very beginnings of the interconnected or National Grid Systems before presenting some escapades in academic research. The first electric lights were the electric candle, which utilized the glow from the arc between two carbon conductors fed from a battery [3]. These were later improved to the incandescent filament supported inside an evacuated glass container. Thus, laboratories, households, streets and public buildings in the late seventeenth century began to be illuminated with the new marvel of the electric light. In 1883 an enterprise was started at the west end of London which originally was intended as a local private lighting installation but ultimately developed into an outstanding example of public electricity supply of great technical and engineering interest. The Grosvenor Gallery installation is one of the pioneers in public electricity supply systems. Using two steam engines with belt drives to two separately excited Siemens single phase 2000 V alternators, the lighting of the gallery was achieved with arc lamps on a series circuit, with an automatic regulator maintaining a steady current of only ten amperes. It gave such satisfaction that requests for supply began to come from neighbouring residents and shopkeepers and electricity supply began to be available for all and sundry. The Grosvenor Gallery Company sought permission to run overhead lines at high tension across the roofs of houses. The demand grew to such an extent that the company had to establish a bigger generating station using two siemens 250kw generators, the largest so far built at that time. This undertaking grew so rapidly and introduced such changes that influenced rapid progress in electrical engineering, [3].

Whilst this enterprise was growing in the U.K, Thomas Edison in 1880 applied for the basic patent for his "power system" with sixty subsidiary applications covering lamps, dynamos, distribution of electric power and auxiliary equipment. He made a distinction between the mains supply and feeders: terms that are today well accepted in Electrical Engineering practice. He formed the Edison Electric illuminating company to operate as a licensee and used New York to demonstrate public electricity supply. Thus, a number of public electricity companies were born in the United States and by 1900 there were about thirty power stations in London alone under the control of both public and private companies. [3]

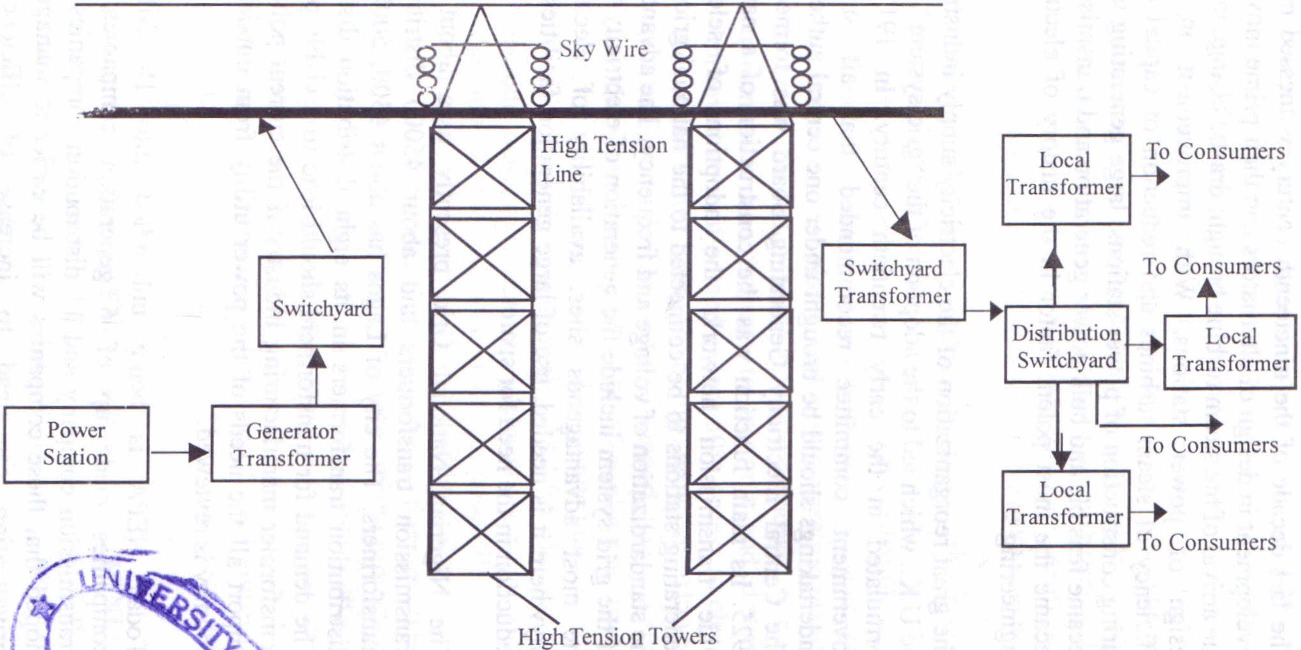


Fig. 2: Electric Energy Transmision and Distribution Model

The last decade of the nineteenth century witnessed rapid development in design of alternators and their prime movers. The arrival of the steam turbine brought drastic change in the design of power stations. With improvement in the efficiency of steam turbines and reduction of capital cost during construction of power stations, large generating units became feasible and bulk power generation and transmission became the most potent factor in the history of electrical engineering.

The great reorganization of the electricity supply industry in the U.K., which led to the adoption of the "grid system", was formulated in the early twentieth century. In 1917, a government committee recommended that all supply undertakings should be brought under one central authority. The Central Electricity Generating Board was formed in 1925. Its main function was the construction of a nation-wide transmission network, the adoption of selected generating stations to be connected to the national grid and the standardization of voltage and frequency. The advantages of the grid system include the generation of electricity from the most advantageous sites, availability of electricity anywhere it is needed, use of large generation facilities and reduction in the need for spares.

The Nigerian National Grid presently uses about 130 transmission transformers and about 45000 distribution transformers. The city of Lagos has about 4300, 500KVA distribution transformers in its eight distribution districts. The demand for transformers should lead to a viable power transformer manufacturing industry if the current policy to import all the needs of the power utility from outside the country is reviewed.

Today NEPA is being unbundled into 18 different companies made up of 6 generation companies, one transmission company and 11 distribution companies. It is hoped that these companies will be easier to manage and privatization can lead to increase of efficiency in performance, can improve sensitivity of the management to the needs of consumers and attract needed investment for expansion. This unbundling is to commence the privatization of NEPA. But we appear to be going back to the early days of power utility operation when several independent power companies existed. Our Independent Power Producers (IPPs) will, in addition to the host generating companies, feed into the existing interconnected transmission facility to ensure that the advantage of the interconnected system is not lost.

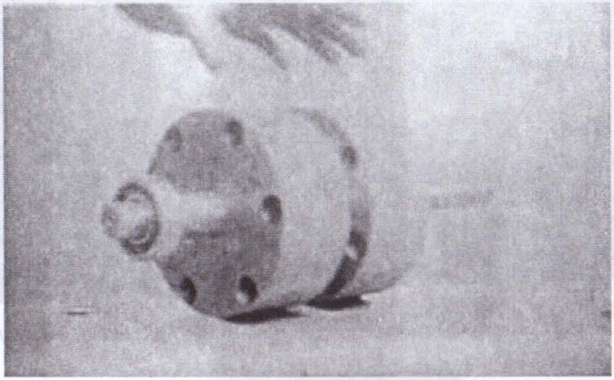
It is pertinent here, to discuss briefly, the prospects of realizing our expectations from the privatization effort. The current expectations is that NEPA should achieve a generation capability of 10,000 MW by the year 2007 from existing over-aged plants, new host generation plants as well as from the Independent Power Producers. A number of transmission line projects to transmit and distribute the improved generation and ensure 50% access to electricity in the country are said to be in progress. However, the technology base required to support these expectations remain undeveloped, as most of equipment requirements have to be imported. The business units that are expected to emerge from the unbundling of NEPA do not appear to include local production of equipment and spare parts. Given the slow pace of take-off of the proposed IPP projects, the high expectation of the nation for additional generation from them may not be realized. Also, the involvement of politicians in the execution of some of the projects on which the growth of the industry is hinged, gives little hope for successful execution. Other issues such as human resource development and the need to achieve some technology transfer through the empowerment of local power industries in the privatization process have not been adequately considered.

PROTOTYPES OF ELECTRICAL MACHINES

The author's interest in electrical machines started with a final year project in 1973 on "Design and Construction of a 6 pole, low speed, homopolar induction machine". The project specification included mechanical and electrical design of the machine and construction of the rotor and end plates as shown in plate 1. The project was executed when the Faculty of Engineering had a UNESCO expert in its Central Workshop. All the materials used for construction of this machine were obtained from the Faculty of Engineering Central Workshop Stores. Today these stores are not adequately funded and our students have to seek private funds for their projects or avoid laboratory based projects completely. This has a negative effect on the quality of graduates produced from the Faculty of Engineering.

As a young lecturer, it became necessary to explore the availability of local materials for manufacture of electrical machines as well as supervise the design and construction [4, 5] of different models of electrical machines shown in plates 2 and 3. These were contributions to local development of skills for design and construction of electrical machines for domestic electrical power industry.

Mr. Vice Chancellor, Sir, it is said that you cannot gain experience by doing nothing. Plate 4 shows the rotor, brush holders and stator of a 4.4 KW D.C. Motor which was internally instrumented using hall plates on the pole faces to enable one investigate the impact of SCR control on DC machines. Oscilograms of the actual flux perturbations and distribution in the air gap of the bridge and chopper controlled DC machine were obtained. Some details of the control equipment used will be discussed later, but it will suffice to state here that this research work earned the author the PhD degree of the University of Birmingham, U.K in June 1980.



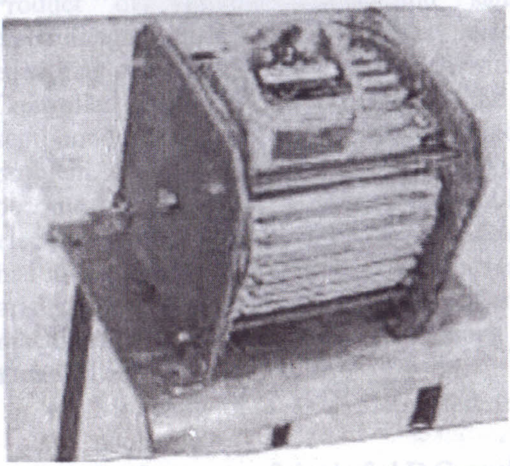
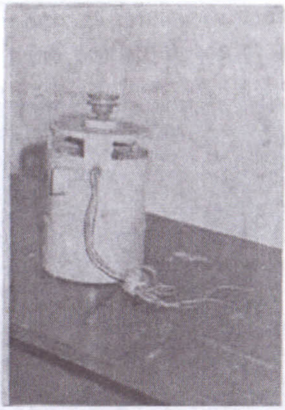


Plate 1: Rotor and Assembly of the 6-Pole Homopolar Induction Machine

Plate 2: Low voltage Transformers: Transformer design and construction project.



Plates 3: A 3-, 2- pole, 5KVA Alternator Electrical Machine Design and Construction Projects.

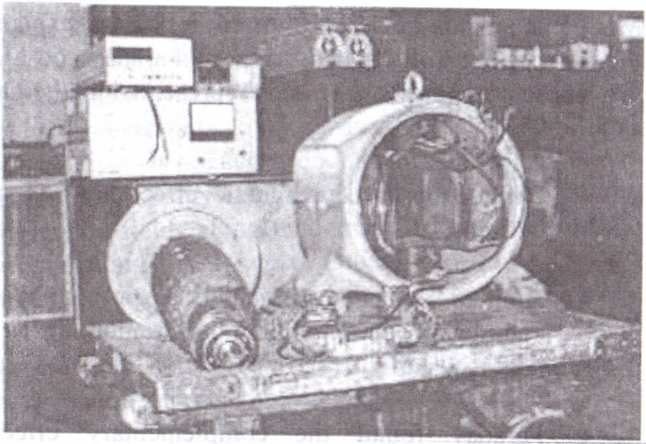


Plate 4: Rotor, Brush Holders and stator of a 4.4 KW D.C. Motor: Research Project on Impact of SCR Controllers on DC machines

6. MODELING AND ANALYSIS OF ELECTRICAL MACHINES.

Product of variable terms and saturation in the electromagnetic structures make electrical machine equations non linear. When controlled with modern Silicon Controlled Rectifier (SCR) equipment, the switching of the semi-conductor devices complicates the non-linearity problem. Adequate modeling and analytical techniques become important for useful prediction of performance of electrical machines controlled by SCR devices. The author has investigated the impact of ripple current and harmonics arising from semi-conductor controllers on electrical machines and made useful contributions in a number of areas. These include:

- Modeling of a D.C motor fed from static power sources ;
- Performance of ripple fed D.C machines;
- Skin effect losses introduced by ripple current;
- Commutation deterioration in thyristor controlled D.C. machines;
- Evaluation of flux perturbations in ripple fed D.C. Machines.

These contributions were published in local and international journals [6,7,8,9].

Many phenomena in electrical machines can be explained by the contributions of Oersted, Ampere, Faraday and Maxwell [3]. These contributions are each represented mathematically as follows:

- Oersted observed magnetic effect near an electric current

  $$B = \mu H$$

- Ampere extended these ideas and formulated a complete theory leading to his circuital law

  $$\int B dl = \mu_o \int J ds$$

- Faraday found the complementary effect that changing magnetic field produces electric current

  $$\int E dl = -\frac{\partial \phi}{\partial t} = -\int \frac{\partial B}{\partial t} ds$$

- Maxwell completed the equations by extending Amperes theory to embrace changing currents as well as constant ones. He combined the basic ideas of electrostatics and magnetostatics into a single Unified theory of electromagnetic waves which are applicable to all materials, conductors and dielectrics.

For a conducting medium:

$$\nabla x H = J + \frac{\partial D}{\partial t} = (\sigma + j\,\omega\varepsilon)\,E$$

$$\nabla x E = -\frac{\partial B}{\partial t} = -j\omega\,\mu\,H$$

$$\nabla.\,D = \rho$$

$$\nabla.\,B = 0$$

For a dielectric medium, σ and ρ are both zero. $\nabla.B = 0$ confirms that in nature there are no sources of B analogous to electric charges i.e. no magnetic charges exist. By manipulating the above equations, this British physicist Maxwell showed that

$$\nabla^2 E = -\omega^2\,\mu\varepsilon E = (-\omega^2/c^2)\,E$$

$1/\sqrt{\mu\varepsilon}$ has the dimensions of velocity from which he concluded that light is an electromagnetic wave propagated through free space with velocity $c = 1/\sqrt{\mu\varepsilon}$. This is one of the brilliant achievements of Maxwell's theory of electromagnetism. It opened a door into the analysis of the propagation of energy in the form of time varying electromagnetic fields along transmission lines and through hollow conducting tubes (wave guides) as well as systems for producing free electromagnetic waves (antennas).

The energy stored in an electromagnetic field is the sum of the electric and magnetic energies, expresses as:

$P= \frac{1}{2} (\varepsilon E^2 + \mu H^2) /m^2$
It can be shown that
$\int_s P da = \int_s (ExH) da$
or $P = ExH$ watts/ m^2

Also the force in a current circuit in a field of density B is

$$F = JxB$$

Thus Maxwell's equations led to a complete set of equations that may be applied to the analysis of electrical machines . These equations confirm that the two phenomena of electricity and magnetism cannot be separated but were aspects of one phenomena of electromagnetism and magnetism is always associated with moving electric charges.
By manipulation of above Maxwell's equations, one obtains the diffusion equation, one of the most useful equations in the field of science.

$$\nabla^2 J = \sigma \mu_0 \mu \frac{\delta J}{\partial t}$$

$$\nabla^2 B = \sigma \mu_0 \mu \frac{\partial B}{\partial t}$$

The diffusion equation becomes field equations in an electrostatic field with potential function, thus
$E = - \text{grad } V = - \nabla V$

This leads to two important equations for field calculations.
The Poison equation $\nabla^2 V = -\rho/\varepsilon_0\varepsilon$
and this becomes the Laplacian $\nabla^2 V = 0$, when the charge density ρ is zero.

Solution of field equations by the finite difference or finite element methods for specified field boundaries provide a method for obtaining field patterns inside electrical machines. Field and mmf patterns offer insight into the electromagnetic action inside the electrical machines. Interaction of fields inside electrical machines when saturation has not taken place in the electromagnetic structures (linear analysis) was the basis of the general theory of electrical machines proposed by KRON, GIBBS and others. Disciples of this theory, ADKINS and HARLEY proposed the modern versions which are today considered mandatory for any versatile and computer based treatment of Electrical machines. Field patterns of electrical machines are not only obtained analytically by solution of the field equations but can be demonstrated using the universal machine instrumented for the purpose. The study of electrical machines at post graduate level today include the use of numerical techniques for solution of field and differential equations associated with different media and coils of the machine structures and relying on boundary and initial conditions imposed on the solutions. [10]

.1 The General Theory of Electrical Machines

Although the general theory of electrical machines began to emerge following the postulates of Gabriel Kron [11] as to the use of tensors in the analysis of electrical machines, its acceptance came after the work of Park [12], which proposed transformations of winding variables from the a-b-c reference frame to the d-q-o reference frame. This universal theory, which gives a uniform treatment of all types of electrical machines, has been the spring board for dynamic analysis of electrical machines and power systems networks [13, 14, 15, 16] and the areas of applications are many.

In a research on the impact of semi-conductor controls on electrical machines, the author postulated that lack of simple methods for predicting some of the losses in an electrical machine had limited theoretical work on additional losses introduced by ripple current. Consequently a coupled-circuit primitive machine equivalent model of fig 3b was proposed as a modification of the Ewing's equivalent circuit of fig 3a, for prediction of the induced currents from the ripple currents.

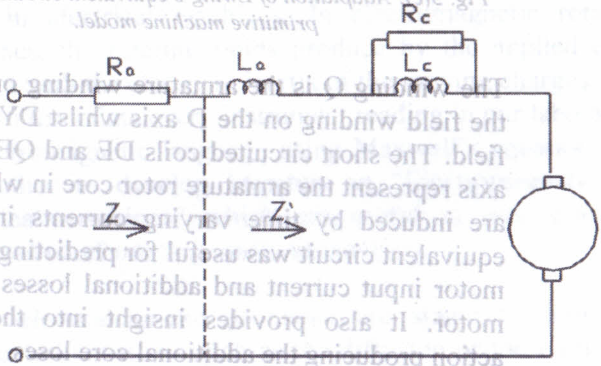


Fig 3(a): Ewing's equivalent circuit for DC machine armature

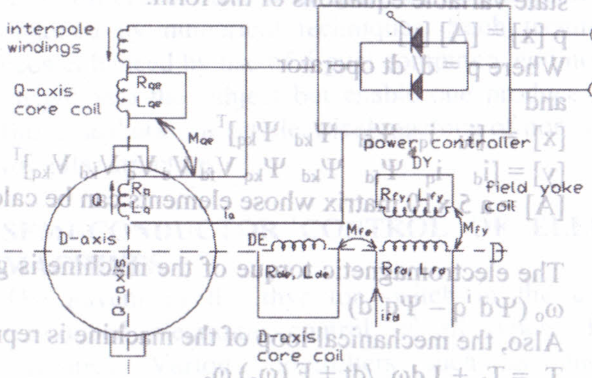


Fig 3(b): Primitive machine model of thyristor-controlled DC machine

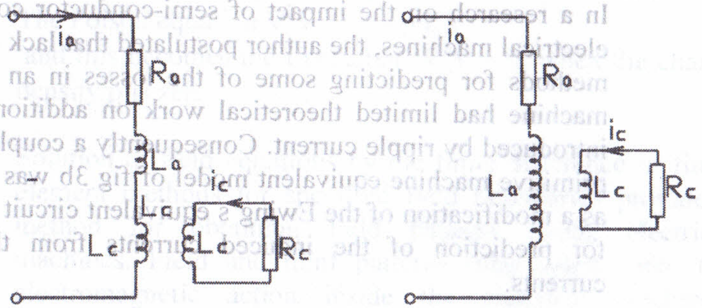


Fig. 3(c): Adaptation of Ewing's equivalent circuit for use in primitive machine model.

The winding Q is the armature winding on the Q-axis, D is the field winding on the D axis whilst DY is the core of the field. The short circuited coils DE and QE on the respective axis represent the armature rotor core in which eddy currents are induced by time varying currents in each axis. This equivalent circuit was useful for predicting the waveforms of motor input current and additional losses in the bridge fed motor. It also provides insight into the electromagnetic action producing the additional core loses.

The conventional voltage and flux equations for each winding of the machine are manipulated to obtain a set of state variable equations of the form:

p [x] = [A] [y]

Where p = d/ dt operator

and

$[x] = [i_d \quad i_q \quad \Psi_{fd} \quad \Psi_{kd} \quad \Psi_{kq}]^T$

$[y] = [i_d \quad i_q \quad \Psi_{fd} \quad \Psi_{kd} \quad \Psi_{kq} \; V_{fd} \; V_d \; V_q \; V_{kd} \; V_{kq}]^T$

[A] = a 5 x10 matrix whose elements can be calculated [17]

The electromagnetic torque of the machine is given by $T_e = \omega_o (\Psi d \, {}^{i}q - \Psi q \, {}^{i}d)$

Also, the mechanical loop of the machine is represented by

$T_e = T_L + J \, d\omega_o / dt + F(\omega_o) \, \omega_o$

The machine speed is included as one of the integral equations of the machine. From the peak value of the induced currents in the coils, the root mean square values of currents and hence the additional losses due to ripple current are predicted. The motor input current predicted from the primitive machine model compared reasonably with those obtained experimentally and from the alternative analytical approach, the piece-wise linear method.

6.2 Finite Difference Solution of Field Equations

Many electrical engineers miss the thrill of applying electromagnetic field theory to power engineering. This possibility is obscured in basic and conventional theoretical work in electrical machines. In electromagnetic rotating machines, the rotating fields produce by the applied emfs interact with the electrical inertia of the moving charges. The drive to formulate every instrument reading in our laboratory in electromagnetic language using Maxwell's equations led the author to develop literature in "Electromagnetics of Electrical machines" which are useful at post graduate presentation of rotating machines analysis.

Many electromagnetic problems are stated in terms of differential equations such as the diffusion or the Laplacian equations. They are reduced to algebraic finite difference equations by consideration of Taylor series expansion of the differential equations. The potential distribution within a finite difference grid with specified boundary conditions is obtained by numerical techniques. Such techniques have been enhanced by use of digital computers and not only give insight into the subject but enable one produce patterns of flux distribution in an electrical machine of non-uniform and irregular structure.

7. SEMI-CONDUCTOR CONTROL OF ELECTRICAL MACHINES

The advent of the thyristor switch in the early sixties introduced electronic control of all types of electrical machines. Various controllers such as: the AC–DC converter, DC-AC inverter, AC-AC cycloconverter, and the DC-DC chopper emerged. With the various circuit configurations of these thyristor based power controllers came a wide range of industrial applications. The application areas include: long and limited range electric traction, industrial drives, frequency converters, induction heating and in various electric power conversion and regulation schemes.

Initial challenges during the authors work on performance data of the control machines were the design and construction of a DC –DC chopper and the Asymmetrical single phase bridge for a 5kw DC machine. These systems were accurately modeled and analyzed and several publications were made in international and local journals [6, 10, 18].

7.1 The Asymmetrical Single Phase Bridge.

The circuit configuration of the asymmetrical single phase converter with its half-cycle equivalent circuit is shown in fig 4(a) and the various intervals of operation illustrating the sequential conduction of the devices to produce the motor input current are shown in fig 4(b).

Equations governing the operation of the converter can be written for each interval (piece-wise linear method of solution) of operation and refer to circuits in which

(i) A steady-state condition has been established to justify repetitive representation of the cycles.
(ii) The thyristors are ideal switches.
(iii) The effects of non-linearities in operation of the machine are included in the parameters of system equations.
(iv) The motor is separately excited.

As a result of the finite source inductance, current in a thyristor fired at an instant α does not rise instantaneously. In the interval $\alpha<x<\alpha+u$, shown in fig 4(b), the thyristor Th_1 forward commutates and its current rises to the value of the motor current, u radians after the thyristor was gated. If the current at the end of the interval is I_{ao}, then it can be shown by solution of the interval equations that:

$$I_{ao} = K_1 \{\mathrm{Sin}\,(\alpha + u - \theta_1.) + \mathrm{Sin}\,(\theta - \alpha)\ \exp(-u/\omega t)\}$$

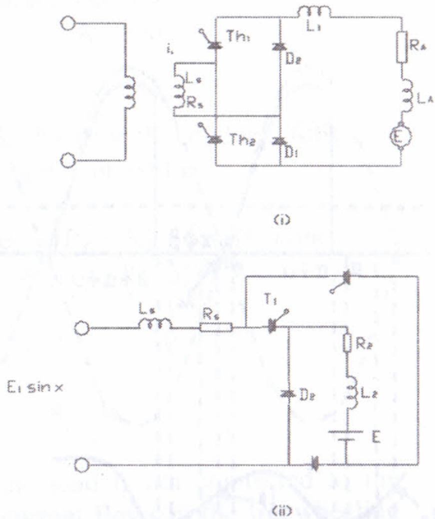


Fig 4(a): (i) Single-phase bridge circuit (ii) with half cycle equivalent

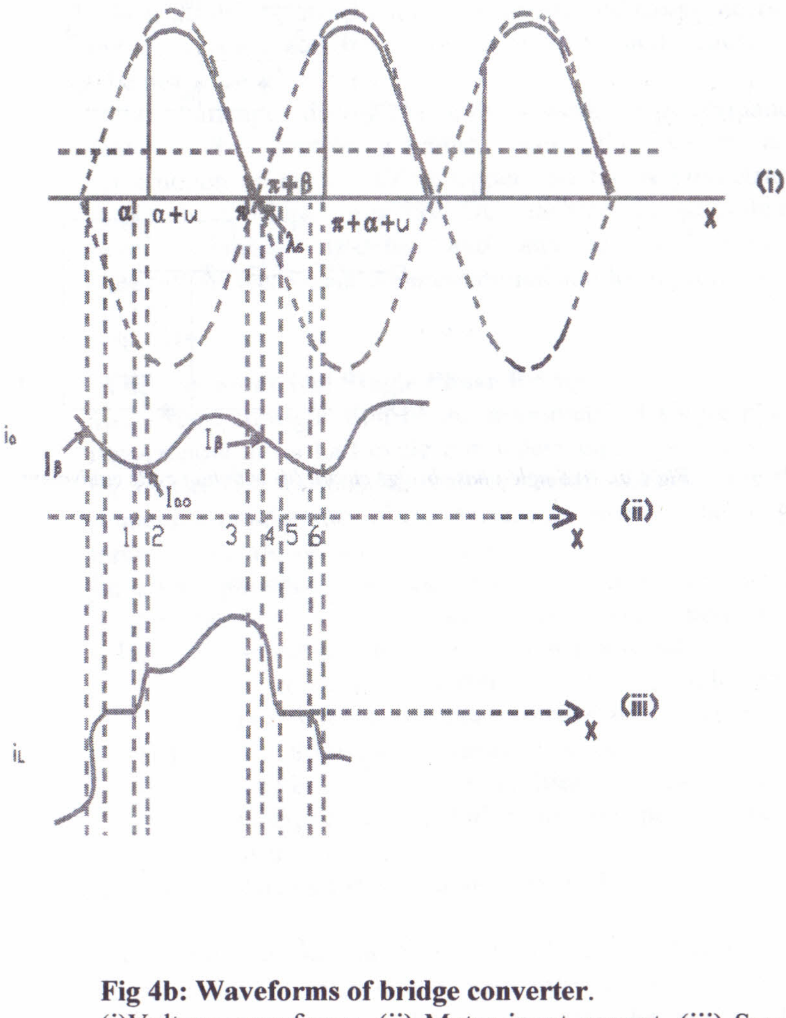


Fig 4b: Waveforms of bridge converter.

(i)Voltage waveforms, (ii) Motor input current, (iii) Supply current 1-2 forward commutation of Th_1, 2-3 conduction of Th_1 , 3-4 angle β, after π for D_2, to become forward biased, 4-5 extinction interval 5-6 freewheeling interval.

Wheres $K_1 = E_1/Z_1$, $\omega = 2\Pi f$
α= delay angle, u = Commutation angle
$\theta_1 = Tan^{-1} \omega L_s/R_s$, $\tau_1 = L_s/R_s$, $Z_1 = R_s + j\omega L_s$
E =motor back e.m.f.

In the interval $\alpha+u<x<\pi$, the thyristor th_1 conducts fully and the motor input current during the interval is:

$$i(x) = K_2 \{\cos\theta_2 \, Sin\,(x-\theta_2) - P\} + K_2 \{ Cos\,(\theta_2)\, Sin\,(\theta_2 - \alpha - u) + P\} exp\{-(x-\alpha-u)/(\omega\tau)\}$$

Where $K_2 = E_1/R$, $\theta_2 = tan^{-1}(\omega L/R)$, $P = E/E_1$

$\tau = L/R$, $L = L_s + L_a + L_1$, $R = R_s + R_a$

In the interval $0< x<\alpha$, the load is not connected to the supply voltage, the motor current flows in the freewheeling circuit formed by the diodes in the bridge and the armature. The current seen by the motor in this interval is

$$i(x) = I_1 \exp(-x/\omega\,\tau_2) - K_3\,[1 - \exp(-x/\omega\tau_2)]$$

$$\text{Where } I_1 = i(x)\Big|_{x=0}$$

$$K_3 = E/Ra, \quad \tau_2 = L_2/R_a, \quad L_2 = L_a + L_1$$

Some variables of the bridge are calculated for any prescribed delay angle by solution of transcendental equations containing them {6}. The solutions require the use of a digital computer and enable one to predict the form of current for any of the values of the variables.

Fig 5 shows the waveform of voltage across the motor load and the motor input current for a practical bridge. The motor input voltage and current are seen to depart from the direct voltage and currents for which the machine is designed. They contain ripple and harmonics, which have deleterious effect on the machine.

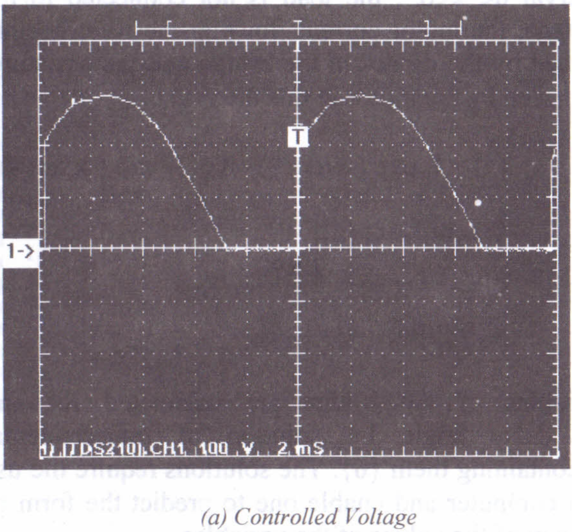
The heating effect associated with armature ripple current is calculated from the explicit expressions of armature current or from the harmonic spectrum of the current waveform. The former approach is more tedious, since the equations are long. If the motor input current is expressed by the Fourier series.

$$i(x) = I_{dc} + \sum_{n=2}^{\infty} (A_n \, Cosnx + B_n \, Sinnx)$$

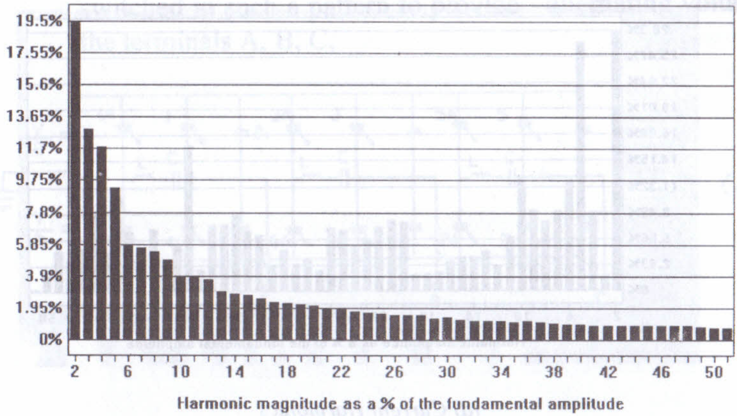
The rms value of the current is:

$$I_{RMS} = (I^2_{dc} + \sum_{n=2}^{\infty} I^2_{n})^{1/2}$$

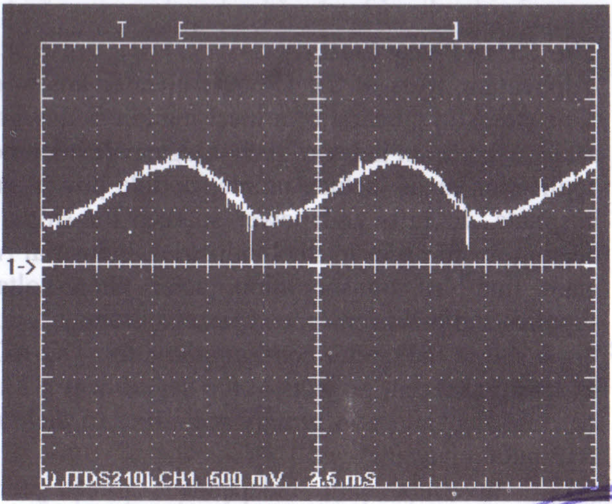
Where $I_n = \sqrt{\frac{A^2_n + B^2_n}{2}}$



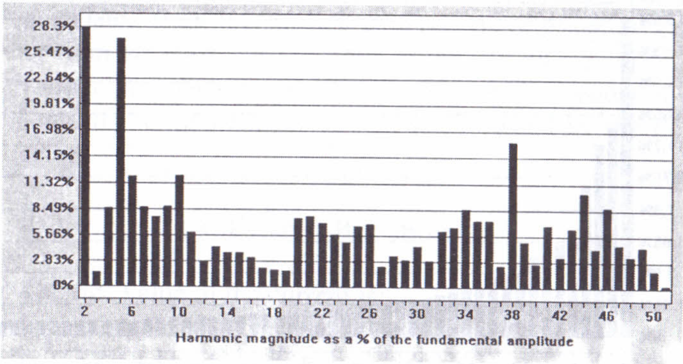
(a) Controlled Voltage



(b) Voltage Harmonics



(c) Motor Input Current



(d) Current Harmonics

Fig 5: Waveform of voltage across motor load and motor input current of a practical bridge with associated Harmonics

7.2 The Three Phase Inverter

Application areas of the DC-AC inverter are so many that the successful creation of a local market in any country can easily become an index of technological development. These application areas include uninterruptible power supplies for hospitals, aircrafts and power sources for ships, induction heating for furnaces in steel industries, industrial A.C drives, main line rail transportation, solar photo-voltaic power supplies and precision speed control systems.

Fig 6 shows the circuit configurations for DC-AC inverters as set up in recent projects in the department [18]. They can be classified into two groups according to their method of commutation as follows:

(a) Inverters with independent forced commutation circuits involving commutation thyristors as in the McMurray inverter.

(b) Inverters with self commutation capability through the inversion thyristors themselves as in the series capacitor commutated inverter.

The conduction patterns of the six inversion thyristors are not discussed for brevity. The inversion thyristors are switched in such a pattern to provide alternating voltage at the terminals A, B, C,

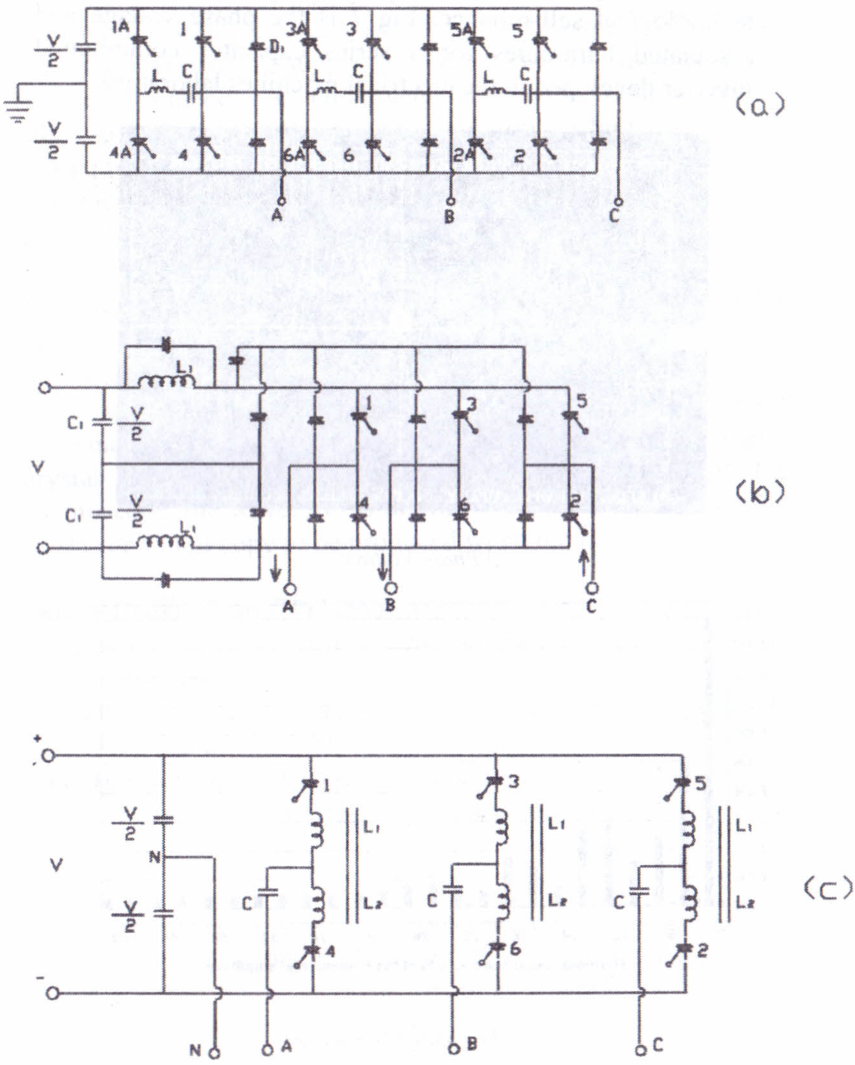
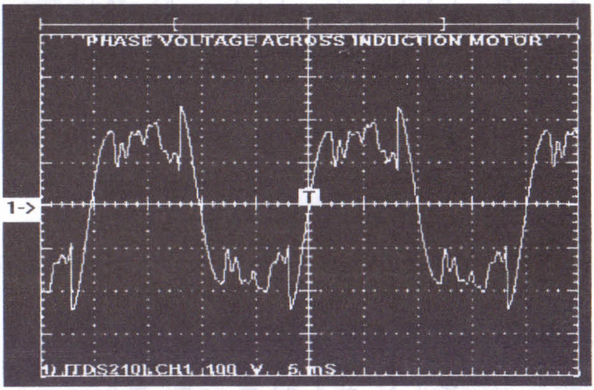
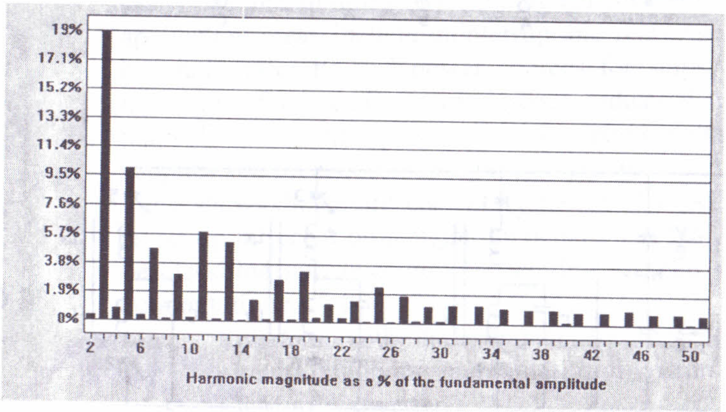


Fig 6: Thyristor circuit configurations for three phase DC-AC inversion (a) McMurray Inverter (b) Impulse Commutated Inverter (c) Series Capacitor Commutated Inverter

The projects have served to transfer the concepts and skills for this technology, which is going to be increasingly adopted as the nation begins to develop the infrastructure for technological self-reliance. Fig 7 is the phase voltage and associated harmonics for a series capacitor commutated inverter developed in the electrical machines laboratory.



(a) Phase Voltage



(b) Voltage Harmonics

Fig 7: Phase Voltage for a series capacitor Commutated 3- ϕ Inverter with associated Harmonics.

7.3 Local Development of Drives

The author would wish to acknowledge the research grants* from the University of Lagos Central Research Committee which assisted in sustaining research work in various arrears of interest. The most outstanding support was for a vision to develop some modern controllers as equipment in the electrical machines laboratory. Plate 5 shows the various prototypes built:

- An automatic voltage regulator for alternators;
- A three phase AC –DC inverter;
- An Asymmetrical single phase bridge; and
- A DC-DC Chopper.

The grants also included acquisition of laboratory equipment for processing associated waveforms into harmonics as well as producing hard copies of waveforms from laboratory oscilloscopes using computer based software and inter-phase equipment. The waveforms are first recorded with the liquid crystal oscilloscope. Using the inter-phase adapter of the oscilloscope, the waveform is digitized and stored in a computer ROM for a hard copy to be produced when required.

Research Grants from CRC UNILAG

1. *Transient stability of machine – Infinite bus systems:*
   Value:- N40, 000
2. *A survey of Drives and Control Techniques in Nigerian Industries: value N40,000*
3. *Development of controllers for industrial and traction Drives: value N51,000 initially; supplementary grant N965,055.00*

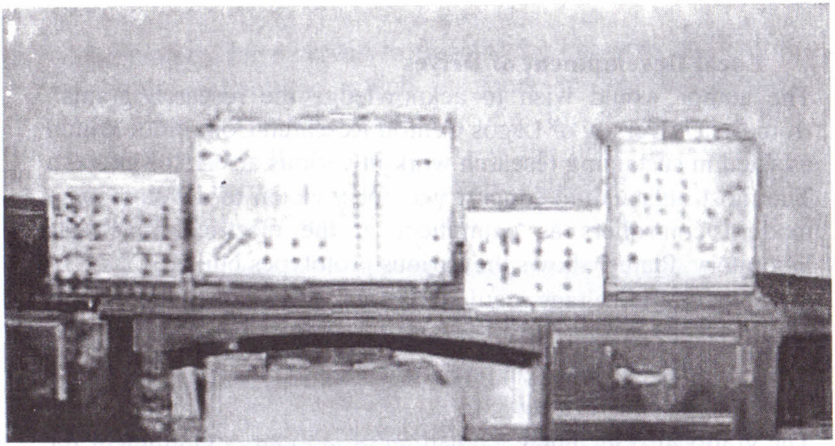


Plate 5: Prototypes of Electrical Machine Controllers as laboratory Equipment.

The waveforms of voltages and current from our prototypes of equipment are non-sinusoidal and contain considerable harmonics. These harmonics are subject of research effort to reduce their magnitude. They create problems for industry which include:

(i) Increased losses and reduced efficiency;
(ii) Mal operation of relays;
(iii) Electromagnetic Interference problems; and
(iv) Poor power factor in power supply systems.

Electromagnetic compatibility of electrical equipment has recently become of interest to the department in the light of increased construction of communication masts and equipment. Expertise is being developed through research and collaboration with experts outside the country. The department of Electrical and Electronics Engineering intends to offer our society some leadership in this area in the interest of public safety.

8. CONTRIBUTION TO UNIVERSITY AND COUNTRY

The impact of our continued effort in the laboratory is that most experiments for practical training of our students have over the years been reviewed and new ones introduced . Controllers have been built as laboratory equipment thereby saving cost for the acquisition from foreign laboratories. A number of projects aimed at development of specialized skills for local industries were embarked upon. These projects include:

- Model of an electric car;
- Local initiatives in Engineering (use of solar energy, local sourcing of raw materials for specified application);
- Codes and standards for engineering practice;
- Re-engineering of imported equipment; and
- Professional ethics in Engineering.

The author has also been in the vanguard for national self-reliance in Engineering and Technology through the professional activities of the Nigerian Society of Engineers. The author has encouraged professional bodies to become the veritable think-tank for policy formulation [12,13]. By studying the design and implementation of government projects in the country, professional bodies can positively catalyze the performance of government and provide data for better performance in future development projects. The author has served the Nigerian Society of Engineers in many capacities and is currently the Chairman of the Codes and Standard Committee of the Professional Development Board of the Society.

9. CURRENT ACADEMIC AND PROFESSIONAL CHALLENGES

The challenges faced by an academic in a faculty of engineering are similar to those faced by an engineer in an active industry in his field of interest. They are both committed to efficient design and operation of equipment and maintenance of professional standards in practice. They are both committed to contributions to knowledge in their fields of endeavour. Attempts to separate them in the past have isolated the Universities from industry and removed the mutual respect and incubation of ideas that can arise from such co-operation.

One welcomes the new developments in University – Industry collaboration at the university of Lagos : The HIVOTEC Nigeria project between the University of Lagos, ABB and NEPA on the one hand and the GSM training facility between the University and Ericsson worldwide are cases of interest. These developments will bridge the gap that has existed in University-Industry collaboration and assist the University produce graduates that meet the needs of industry. It should be a model for other universities in the country to copy.

It is an increasing trend world wide that only few graduates of Electrical Engineering want a career in Power Engineering. The global interests in Information Technology are exacerbating this trend. The department of Electrical and Electronics Engineering is currently looking at ways of sustaining the interest of graduates in Power Engineering and attracting more of them to postgraduate research. One way of achieving this is to provide financial support for such education. We need the help of the power industry in Nigeria to achieve this and it is hoped that the HIVOTEC Nigeria project is a development in this direction. It is expected that this project can assist the department to

- Acquire additional equipment for teaching and research.
- Extend the capacity to find solution to local problems through field work.
- Attract students to Power Engineering careers through funding of industrial training (field work) activities.
- Contribute to development of local standards for engineering practice.

The department is collaborating with industry to develop models of engineering systems (which are vital to the industries) in the laboratories so that training received by our graduates are adequate for the needs of public utilities. Examples of these models in the power sector include:

1. A micro machine infinite bus-bar system with peripheral equipment such as the speed governor system (closed loop speed controller) and automatic voltage regulator.
2. A transmission line simulator with modern relay protection schemes (modeling of various lines in the country).
3. Development of an EMC test facility.

These systems are expected to provide the basis for more interactive relationship with industry especially NEPA.

The department seeks further collaborative work with industry so as to contribute to solution of identified local technical problems. Such research should be beneficial to the University as well as the benefiting industry who should contribute to the funding of the research.

The Engineer remains another potential on the long list of Nigeria's resources waiting to be tapped [21]. The Nigerian government has over the years failed to give the Nigerian Engineers the task of meeting the engineering challenges of the nation. No wonder we have been unable to create jobs for our young graduates. Engineers are continuing the effort to reverse the above situation. As a Fellow of the Nigerian Society of Engineers, I am fully committed to work with professional colleagues to ensure that this trend is reversed.

There are little engineering development activities taking place in our public utilities and even the private sector industries. Most of our industries rely on finished goods and equipment from outside the country. Raw materials exported from our country are returned to our markets after being processed abroad. There is need to be able to assess what technologies have today been acquired by our Engineers and the progress made in our much vaunted aspiration for self reliance. Engineers should lead the way in technology acquisition and provide the "Missing link" in our current efforts at technology acquisition. This missing link can be provided by increased local content in our industries, local fabrication of spares and development of local standards for all equipment affected by environmental factors [23].

10. CONCLUSIONS:

Electrical machines control and their peripheral equipment could be the springboard for developing the skills for operating and maintaining modern industrial infrastructure. However some national policies have tended to sabotage the much-avowed policy of self-reliance in Engineering and technology. The University research laboratory can develop the capability for producing prototypes of industrial equipment. Effort should therefore be made to increase funding of University research laboratories and increase motivation of researchers to contribute to solution of problems of industry and outer society.

11. RECOMMENDATIONS:

Whilst education enables one to inherit the past, it should also assist one to recreate it. In the light of the above discussions of the author's research and professional activities, it is obvious that more effort is needed today to recreate the past. I therefore humbly make the following recommendations to the Universities and Engineering Professional Bodies.

(i) As a means of arresting the declining interest in doing useful practical projects in our Universities, there is need to increase funding of Engineering laboratories. The Universities should revert to the culture of providing consumables needed by students for their final year projects.

(ii) It is my view that young lecturers should start their careers in the laboratories. This should enable them develop the capabilities to demonstrate the concepts of their lectures in the laboratories.

(iii) To encourage increased effort in developing "local initiatives in Engineering", public utilities should create the position of "Engineering Development Directors" who should endeavour to increase in-house production activities and "local content" (materials and spare parts) in production requirements.

(iv) We join our colleagues in the Nigerian Society of Engineers to call on the Federal Government to carve out roles for Nigerian Engineers in major projects done in this country.

(v) Engineers should midwife policies that ensure efficient management of resources and direct effort to areas of comparative advantage i.e.

areas that Nigeria can compete effectively with the rest of the world to the benefit of Nigerians.

(vi) Engineering Education for National Development requires that graduates are trained to solve the problems in society. As part of a University's Community Service, engineering students should be engaged in projects that meet the needs of society e.g. rural electrification, solar P.V supply systems, traffic lights, drainage designs and construction etc. This is already feasible in electrical power supply system maintenance and computer assembly and networking.

(vii) The Nigerian Society of Engineers should support "local initiatives in engineering that can lead to increased "in-house engineering development works" in Nigeria and "local demand-driven research and development" in Universities and research establishments.

(viii) University faculties of Engineering should collaborate with the NSE and Standards Organization of Nigeria to contribute to development of Standards for Engineering practice and develop the needed Standards infrastructure for Nigeria.

12 EPILOGUE

One of the factors that influence industrial development, which Electrical Engineering has bequeathed to mankind, is cycle time. Time after time we do a number of things repeatedly. The frequency of our AC supply is 50 Hertz. Teachers often have to pass some volume of information to students over and over again. Every manufacturing engineer knows that the more you make a product, the more opportunities there are to learn how to make that product more efficiently. We have at the University of Lagos recently tried to reduce the time for our students to complete a cycle of registration exercise. The current revolution in the GSM technology is because engineers are able to transmit and receive signals at higher frequencies or shorter cycle times. When we shorten cycle times, we create faster machines and increase production or gain competitive advantage. For the engineer the race is for the swift. Industry seeks to shorten cycle times through professional development of staff and support for research leading to breakthroughs that come from collaborative partnership with Universities.

Engineering Education has over the years adopted a methodology of "learning and doing". Rapid learning happens when we "learn" and "do" at the same time. This is why the Faculty of Engineering has a complement of laboratories for this training process. Without the "doing" aspect of engineering education, the various systems used in this lecture to illustrate applications of electrical machines would not have been developed and progress in technology would have been slower. In the information age, we can engage in simultaneous learning and doing on an unprecedented scale.

It is clear that the slow pace of technology development in Nigeria has not only come from the failure to implement policies on science and technology but also the trend to reduce the zeal for the "doing" aspect of education in our laboratories.

The kind of funds that develop facilities for research centres of excellence are not usually obtained from a common pool that every faculty of a University draws from. In the eighties we sought for N750,000 to develop a modern Micro-machine system in the machines laboratory but could not find the money. Today it will cost about ten million naira to develop the same research training facility. Initial estimates on the EMC test facility we are thinking of at the Electrical Electronics Engineering Department is about five to ten million naira to achieve that goal. We shall continue to ask for increased funding for engineering education and increased interest in engineering development activities in our universities, research centres and public utilities.

13. ACKNOWLEDGMENTS

I wish to first thank the Almighty God, the creator of all things visible and invisible, the omnipresent and omniscient, the source of all wisdom and knowledge, for sparing my life from the day I was born to this day. I was born at a time when my home community did not welcome twins. But by the Grace of God our parents had embraced Christianity and decided that we would live. I thank the Almighty for the many opportunities that I had in life and whatever I may have achieved to this day.

My returning to the University of Lagos as a graduate Assistant in 1973 was an act of God. I thank my teachers Dr. O Ajayi and Dr. A.C Jani who God used to make this possible. I thank the British Council and the University of Lagos for a scholarship and study leave during the postgraduate training. I thank the Federal Government of Nigeria for a scholarship during the PhD research programme.

I most heartily thank my teachers from primary schools, secondary schools and the three Universities I attended for their notable inputs in my educational development. I make special mention of Prof. Brian Mellitt, the supervisor of my PhD research, who successfully showed that the University Engineering lecturer and industry management could switch engineering roles.

I thank my colleagues in the department of Electrical and Electronics Engineering for the co-operation they have given to me and the progress taking place in the department today.

My Parents, Mr. Alfred Uwajimogu Okoro and Mrs. Priscilla Ada Okoro (of blessed memory) are special for successfully carrying the burden of rearing a large family of ten children. We appreciate them for their investments in the education of their children and setting the record in our community of all their children being graduates. I thank the members of the great Okoro family for always being there for me and

particularly my twin sister Mrs. B.N Okechukwu for her regular support.

Finally, I thank the Almighty God for my wife and children and for His grace and provisions for the family. The companionship, friendship and love of my wife Stella (Star) have been precious and priceless. She has been as constant as the northern star. Our children, Chibuzo (Electrical Engineer, Unilag), Amarachukwu (Accountant Unilag,) Ndubuisi (Aerospace Engineering and Mechanical Engineering) and Nnadozie (Pharmacy Student, Unilag,) have been a great pride to us. I thank the University of Lagos for various forms of support whilst my wife and I were striving to bring up our children.

Mr. Vice Chancellor, Sir, distinguished members of this great community, my professional colleagues, friends, family members and well wishers, I thank you very much indeed for being part of my day and for your much valued attention. God bless you.

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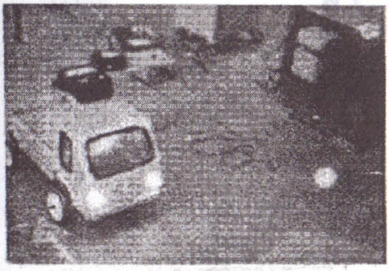
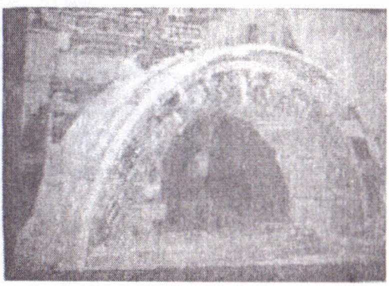
PHOTO PANORAMA

ELECTRICAL MACHINES IN THE SERVICE OF MAN

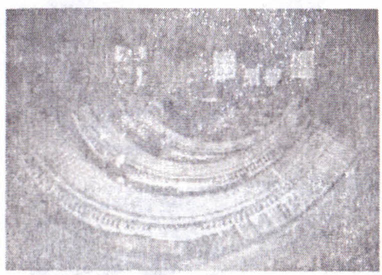


Model Electric motor driven car.

Armature of DC Motor with commutators and band wire for rod and bar mill drives[1]

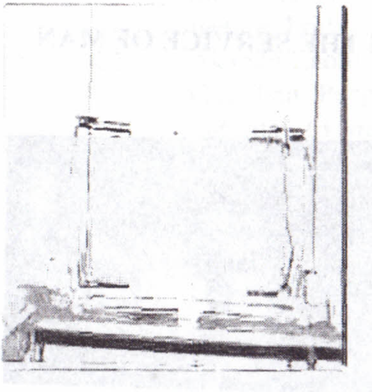


Large DC Motor Stator for rolling Mills showing compensating windings[1]

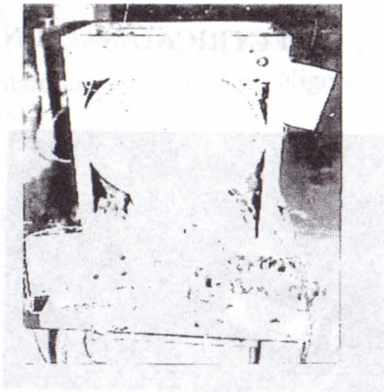


Segment of stator of water-wheel Generator (Hydro-generator) [1]

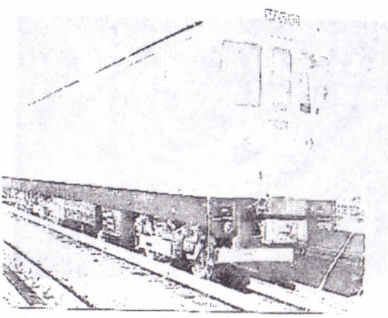
[1]*Courtesy GEC Machines Ltd. Rugby England*



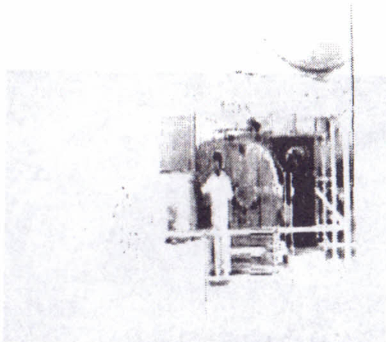
Motor Driven automatic slide Door.



Redesign of washing machine 3-speed control.



Chopper controlled London underground Train.



Drive Motor with Gear system For a cement kiln

University of Lagos Press