University of Lagos Press

UNIVERSITY OF LAGOS, NIGERIA

Inaugural Lecture Series 2011

TOPIC:

POWER SYSTEM CONTROL AND AUTOMATION: THE CHALLENGE OF RELIABLE POWER SUPPLY

By

PROFESSOR FRANK N. OKAFOR

POWER SYSTEM CONTROL AND AUTOMATION: THE CHALLENGE OF RELIABLE POWER SUPPLY

An Inaugural Lecture Delivered at the University of Lagos
Main Auditorium on Wednesday, 16th November, 2011

by

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University of Lagos Press

Published 2011

by

University of Lagos Press
Unilag P. O. Box 132,
University of Lagos,
Akoka.

ISSN: 1119-4456

PREAMBLE

The Vice-Chancellor, Deputy Vice-Chancellor (Management Services), Deputy Vice-Chancellor (Academic & Research), The Registrar, the Provost, College of Medicine, Dean of Engineering and other Deans here present, Members of Senate, Principal Officers of the University, other Distinguished academic colleagues, the Honorable Minister Power, The Chairman, Nigerian Electricity Regulatory Commission (NERC), The Director General, National Power Training Institute of Nigeria, Invited Guests, Respected Students, Members of the Press, Distinguished Ladies and Gentlemen.

It is a source of immense joy that this day has become a reality. We therefore, thank God for His mercies and pray that He continues to shower his blessings on us. Having reached this far in the persistent struggle for existence, I have come to realize that what a man/woman becomes is a combination of hard work and providence. Even hard work is by His grace, having told "man" in the Garden of Eden," By your sweat, you shall live". Mr. Vice-Chancellor sir, may our sweat produce good fruits.

I fully subscribe to the school of thought which argues that an inaugural lecture must be celebrated to formalize the commencement of a professorial career in a university. What may differ in diverse educational cultures is the mode of presentation and the contents. Mr. Vice-Chancellor sir, between 2001 and 2003 I attended two inaugural lectures at the Technical University of Chemnitz and Technical University of Dresden respectively, both in Germany. It is the culture of German Universities to appoint Engineering Professors from the industry. Hence, both lectures took place within 48 hours of resumption of duty, and contained mostly the vision of the new appointees in terms of research and growth directions. This lecture will tow the line of the German Professors in content for one simple reason; It is a rare privilege to engage the attention of the University of Lagos Management for one hour and I don't intend to squander it on self eulogy and rhetorics.

Since 2005, the terrain of the Nigerian Electricity Supply Industry (NESI) has been changing very fast, starting from the unbundling of the Vertically Integrated Utility (VIU) called National Electric Power Authority (NEPA) to creating 18 successor companies which are meant to be privatized except one, the Transmission Company of Nigeria (TCN). With the passing into law of the Electric Power Sector Reform Act by the National Assembly in 2005, the Nigerian Electricity Regulatory Commission (NERC) was constituted with the sole responsibility to regulate activities in the power sector including tariff regimes. In 2007 NERC introduced the Multi Year Tariff Order (MYTO), aimed at providing economic tariff that will attract investments to the power sector. Concerted efforts are being made to improve generation through licensing of about 35 Independent Power Producers (IPPs) and some government funded projects like National Integrated Power Project (NIPP). Similar efforts are easily noticeable in the transmission and to some extent, distribution sectors of the power delivery chain. In all these, the average Nigerian resident desires and indeed deserves uninterrupted supply of electric power in the right quantity and quality. This is yet to be achieved. In recent times, this failure in power supply reliability has been put squarely on the door step of inadequate power generation. However, some of us who are close to Nigerian power system operations know that whenever the supply capacity maintains about 4,000 MW for a few hours, the system suffers great instability and either partially or totally collapses. Therefore, beyond measured inadequacies in the transmission and distribution network, most system collapses are direct consequences of low level of automation and inefficient control mechanisms. It is against this background that the University of Lagos management should be commended for initiating discourse on this important national challenge through this inaugural lecture titled: **POWER SYSTEM CONTROL AND AUTOMATION, THE CHALLENGE OF RELIABLE ELECTRIC POWER SUPPLY.**

INTRODUCTION

Electricity has become the driver of societal comfort and growth. This is so because electricity is the most useful form of energy. Since modern life is technology driven, and technology depends on electricity for its operations, it follows that life without this form of energy is miserable and primitive.

Conventional electric power is obtained from generating stations which are usually remote from the consumption centre. The common generating plants utilize hydro, steam, gas or nuclear energy to produce electricity and are linked with the consumers through transmission and distribution network (often called grid network) to form what is called an Electric Power System. It must be added here that due to advances in technology, some renewable energy based electric power generating plants like wind and solar energy power plants can now be connected to the grid network, sometimes at subtransmission or even distribution voltages. An Electric Power System therefore, consists of a linkage of generators, connected to the load through Transmission and Distribution networks.

The primary duty of an electric Power System is to supply the power demanded by all the connected loads in the most efficient manner. Here, efficiency is a function of the economics of system operation. However, the supplied power must, in addition to continuity, conform to certain minimum requirement with regards to quality, such as constant voltage and constant frequency. This is because every electrical equipment is designed to operate at a given voltage and /or frequency within specified tolerance limits. The quality specification on contemporary power system is made more stringent by the advent of high tech equipment with their tight tolerant limits. In order to derive the best service from this equipment, it is vital that the quality of power supply be maintained high.

Mr. Vice-chancellor sir, the quality of power delivered by the Nigerian Power System is not high. Indeed, it is below acceptable standards. The cost to the nation is enormous;

some industries have closed shop and moved over to Ghana, high cost of running business including production of goods, high level of youth unemployment with attendant increase in crime rate, general discomfort of the populace especially those living in high density areas, squandering of national wealth through the operation of small petrol /diesel generators (fuel cost is subsidized), damage to national psyche, severe damages to domestic and industrial equipment etc.
The quality of power supplied by a given power system may be ensured in two ways.

(a) The installation of several generating plants scattered all over the power system area such that for any fault, there still remains enough readily available generating capacity to maintain stability.
(b) The selection of appropriate control strategy such that any fault is arrested fast enough to forestall a sustained degradation of the nominal voltage and /or frequency.

In Nigeria the issue of increased generating capacity has gained a lot of attention. This is evidenced by the recent scramble for independent power projects and the concerted effort of government in the execution of power generating projects like the NIPP, the second phase of Geregu and Omotoso power plants, to mention a few.

Mr Vice-Chancellor sir, may we recall at this juncture, the events that took place in the Nigerian power sector between 1989 and 1993. After the final commissioning of Egbin steam plant in 1987 and Shiroro Hydro plant in 1989, Nigeria had excess generating capacity and everybody heaved a sign of relief. Yet in her 1989 annual report, the National Control Centre (NCC) Oshogbo reported 24 system collapses. However, in 1990, the Vertical Integrated Utility (VIU), the National Electric Power Authority (NEPA) appointed Engr. Seke Somolu, the General Manager (Transmission) in charge of the whole country. He not only continued the review of the protective arrangement which he started as the Director of Protection, Control and Metering (PC&M), but also commenced the upgrading of the Supervisory Control and Data Acquisition

(SCADA) system as well as maintaining the integrity of the communication channel through power line carriers.

In other words, Engr. Somolu improved the system automation by installing new SCADA equipment and reviewed the control structure which included appropriate relay settings, a program that continued till late 1991. The result reduced rate of system collapses in 1990 and 1991 and by 1992 there was zero total system collapse. Most black-outs in 1992 were due to some localized fault as a result of over-stretched distribution infrastructure. In a typical Nigerian fashion, by 1993 several other transmission general managers were appointed with the direct consequence that the control structure became once more un-coordinated and system performance started to degrade. The rest is history.

Against the above background, it can be argued that where we are today in our quest for reliable electric power supply is like history repeating itself. In recent times, the number of system collapses has gone very high [1].

As pointed out in the preamble, a situation where our power system struggles to sustain 4000 MW supply capacity for a reasonable length of time shows that the cure to our unreliable power supply situation goes beyond increased generation.

Mr. Vice-Chancellor sir, the inadequate attention paid to system automation and control infrastructure is a major challenge to reliable power supply in our dear country. The title of this lecture is hereby justified.

Furthermore, taking the Nigerian power network as a typical example, it is easily observed that a power system is a complex entity which calls for a multi-disciplinary approach to the solution of its failure challenges. This lecture will now proceed to discuss the multifaceted nature of modern electrical engineering with a view to highlighting emerging areas where manpower is lacking. The research vision of the author, where

the emphasis will be laid more on problems yet unsolved than the modest results already obtained.
Finally, a few thoughts of the author on structural and academic adjustments necessary for this great University repositioning herself for the emerging Nigerian Electricity Supply Industry (NESI) will be presented, to be followed by some other recommendations.

ELECTRICAL ENGINEERING

Electrical Engineering is a field of engineering that generally deals with the study and application of electricity, electronics and electromagnetism. The field first became an identifiable occupation in the late nineteenth century after commercialization of the electric telegraph and electrical power supply. It now covers a range of sub-topics including power, electronics, control systems, signal processing and telecommunications [2].

According to historical records, the 19th century witnessed a lot of giant strides in electrical science research. Notable among these is the work of Georg Ohm (1827) who established the relationship between the electric current flowing in a conductor and the potential difference (voltage), the discovery of electromagnetic induction by Michael Faraday in 1831 and the publication in 1873 of a unified theory of electricity and magnetism by J. C. Maxwell in his book *"Electricity and Magnetism"*. Based on the above discoveries, we now have the famous ohms law which defines Resistance as the ratio of voltage to the current flowing in a conductor; the Faraday's law of electromagnetic induction also known as the "flux cutting rule" and the well known Maxwell's equations. At this time, electricity was studied as a branch of physics.

However, in 1882, the Darmstadt University of Technology (DUT) in Germany established the first Faculty of Electrical Engineering and also appointed the first chair. Even Massachusetts Institute of Technology only commenced the offering of Electrical Engineering as an option within Physics Department in the same year. DUT finally commenced the first

full course of study in Electrical Engineering in 1883, same year with Cornell University, closely followed by University College London which established the 1st chair of Electrical Engineering in the United Kingdom in 1885.The first Department of Electrical Engineering in the USA was established by the University of Missouri in 1886.

Mr. Vice-Chancellor sir, distinguished ladies and gentlemen, the University of Lagos established her own Department of Electrical Engineering in 1964, forty seven years ago or eighty-one years after the world's first Electrical Engineering Faculty was founded. The performance of our own Department will be x-rayed later in this lecture. Now let us look at other sub-fields of Electrical Engineering.

POWER ENGINEERING

This is a branch of Electrical Engineering that deals with the generation, transmission and distribution of electric energy as well as the design of such associated equipment as transformers, electric motors, electric generators and their interconnection with each other. In recent years, due to increase in the world population and developments in technology, electric power grid systems have become very complicated and typically non-linear which parameters vary with systems operating point. Consequently, control burden has increased and precision demands on modern power system automation tools has become very stringent. Renewable energy generation is also being promoted to connect to distribution networks in what is conventionally called Distributed Generation. In some cases the renewable generating systems feed remote loads and are called stand-alone systems. Against the above background, Power Engineering now includes such other subfields as High Voltage Engineering, High Current Engineering, Electromagnetic Compatibility, Distributed Generation and Power Electronics [5].

ELECTRONICS ENGINEERING

Electronics Engineering is an offshoot of Electrical Engineering which deals with the design and testing of electronic circuits that deploy the properties of circuit components like resistors, capacitors, inductors, diodes and transistors, to achieve a prescribed functionality. Early electronic circuits included tuned circuits, for filtering radio signals, television circuits, radar and commercial radio circuits. Prior to Second World War, radio engineering was more popularly used than electronic engineering. In post war years, several more consumer devices emerged including computers, microprocessors, modern television etc, while discrete components gave rise to integrated circuits. As a result, the subject name changed to electronic engineering. Later advances in fabrication technology gave rise to fields like microelectronics which deals with the design and microfabrication of electronic building blocks, down to the microscopic level as found in integrated circuits. Nanoelectronics is the further scaling of devices down to nanometer level. Electronic systems exist in analog or digital form.

SIGNAL PROCESSING

Signal processing involves the analysis, synthesis and manipulation of signals which may be analog or digital in nature. Analog signals vary continuously with the input information, while digital signals vary according to some series of discrete samples of the information causing the variation. Processing of analog signals may consist of amplification and filtering of audio signals or modulation and demodulation of signals for telecommunications. Digital signal processing may consist of compression, error detection and error correction of quantized signals. DSP processor ICs are found in such electronic equipments as Hi Fi audio equipment, GSM mobile phones, MP3, camcorders etc.

TELECOMMUNICATION ENGINEERING

Telecommunication Engineering deals with the transmission of information across a channel such as coaxial cable, optical fibre or free space. It is now difficult to draw a line between

electronics and telecommunication since the design of electronic devices used for telecommunication like transreceivers, GSM handsets, modems etc. fall within this field. Also with recent developments in computer communication, it appears that both telecommunication and computers have merged.

CONTROL SYSTEMS ENGINEERING

By definition, a control system operates on a plant so as to force the plant to behave in a prescribed manner. Usually the control engineer captures the salient features of a dynamic system (the plant) to be controlled in an abstraction called a mathematical model. This model is analysed, and based on its behaviour, the engineer designs a controller which will force the plant to behave in a desired form. Feedback or feedforward signals are deployed for control system design while implementation is in form of electric circuits, digital signal processors, microcontrollers and Programmable Logic Controllers (PLCs).

HISTORICAL PERSPECTIVE

One can rightly say that control engineering is as old as humanity, since at one time or the other, man had a cause to want to control nature. For instance, in the early days of human existence, supernatural powers were invoked in attempt to control certain natural phenomena, like rain, lighting and even flow of rivers. Also during the execution of wars, special leaves and birds' feathers were attached to the rear end of arrows and spears to enhance their accuracy at hitting the target. This is similar to automatic guiding of missiles in modern warfare [6].

In contemporary society, control systems engineering permeates all facets of life. The automatic toaster, the robot, the space vehicles, the computer, the micro-processor and various industrial gadgets are all examples of existing control systems. Modern missiles can now hit targets several kilometers away with precise accuracy. Indeed, that man had been able to venture into space is a direct consequence of advances in control systems engineering. Also the application of control systems theory and practice in such fields as navigation, aviation, communication, automobile technology, medicine, industrial production, artificial intelligence (cybernetics), crime prevention and detection etc. has yielded tremendous advancement in these areas.

Surprisingly the development of a unified control theory as an independent field of study did not start until the 20th century [7,8]. From the construction of the flyball governor for steam engines in 1788 by James Watt [8], intuition and empirical techniques were used in the design of control systems – usually for position control. The first mathematical consideration of a control scheme is credited to Maxwell, (though more known in field theory) when in 1868 he made an analytical study of the stability of James Watt's flyball governor. This was followed by a more detailed solution of a third order flyball governor by a Russian scientist Wischnegradsky in 1876 [8]. A year later Routh [9] established a more general stability criterion for linear feedback control systems in terms of "probe functions", to be followed by the determinant criterion of Hurwitz [10] in 1895, where, for a system to be stable, the determinants of the "Hurwitz matrices" must be positive. These two criteria were used to ascertain whether a given system is stable in the absolute sense and therefore, the question of relative stability (i.e how stable a system is), remained unsolved. However several other developments took place from this time on [11,12,13,14].

A major breakthrough in the design of control systems came in 1932 when the first frequency response method was introduced by Nyquist [15], while investigating the characteristics of certain communication networks. He related the stability of a feedback system to the number of clockwise encirclements of the (-1 + jo) point on the complex q (s)- plane as the variable 's' traverses the 'Nyquist contour'. Two years later Hazen [16], applied Nyquist's work to position control systems and for the first time used the term 'servomechanism'.

Moreover, about the end of the Second World War in 1945, Bode [17] came out with yet another frequency response method which is derivable from the postulations of Nyquist but is simpler to use. The introduction of the root locus techniques by Evans [18] in 1948, where the trajectory of each pole of the closed loop system (transient response modes) as the gain varies, is investigated, availed the control engineer with a method for direct synthesis. Thus these developments form the nucleus of classical control theory and lead to the design of systems that are stable and satisfy a set of arbitrary performance requirements. They constitute an invaluable tool in the design of linear single – input single – output (SISO) control systems till the present day.

Therefore the classical control theory is based on the complex function theory of mathematics. It represents a system by high order differential equations (usually in the Laplace domain), uses pole-zeros in analysis, frequency measurements in identification, trial and error in design and indirect approach in optimization. The main mathematical tool is the Laplace transformation and initially analog computers were used extensively.

However as engineering systems became more complex and multi – input multi – output (MIMO) systems emerged, a new concept was introduced in the late fifties which was to acquire the name "Modern Control Theory". This is based on the concept of 'state' originally developed by Poincare and Liapunov several years ago in the field of classical mechanics [19]. With the notion of controllability and observability introduced by Kalman [20], this state variable approach became a very important strategy in the design of multivariable systems.

Over the past three decades a lot of research had been done on Linear multivariable feedback theory and its application to the design of feedback MIMO systems. This resulted in new approaches being developed and these fall into broad

categories; the vector time response and the vector frequency response methods.
The vector time response methods include modal control introduced by Rosenbrock [21] in 1962, where, by tuning the input vector of a system by linear feedback of the state vector, prescribed eigenvalues are associated with dynamical modes of the resulting closed loop system. The pole assignment technique introduced by Woham [22], is closely related to modal control in which closed – loop poles of the system are located at desired positions through state variable feed-back. Also in this group is the optimal control developed by Pontryagin [23] with his "maximum principle" and Bellman's work on dynamic programming [24]. Recovery of signals contaminated by noise through filtering techniques introduced by Kalman [25] and Weiner [26] also fall into this category of design methods.

On the other hand, the vector frequency response methods include Rosenbrock's Inverse Nyquist Array Techniques [27], where the dominance, stability and performance of the system are determined from the frequency response of the plant. One other prominent technique is Macfarlance's characteristics loci [28] method, which determines the stability and performance of the system from frequency loci of the eigenvalues of the system transfer function. However these are natural extensions of the classical techniques of Nyquist and Bode to the design of MIMO systems, since they aim at minimising the interaction between the loops of the multivariable system. They have been found to be very practical provided this problem of loop interaction is properly handled [29,30].

In general the modern control theory represents a system by a set of first order differential equations, uses linear transformations in analysis, Liapunov's theory in stability studies, time domain measurements in identification and the direct approach in optimization. The main mathematical tool is matrix theory and digital computers are usually employed.
The control engineering problem is concerned with the design of control systems with prescribed performance specifications.

These performance indices are related qualitatively to all or a combination of the following [31]:

(i) System stability
(ii) Speed of response
(iii) Steady state accuracy
(iv) Dynamic accuracy
(v) Insensitivity to parameter variations (system integrity)

Thus the engineering control problem may be divided into the following steps:

1. A set of performance specifications exists;
2. A control problem exists as a result of these performance specifications;
3. A mathematical model of the physical system is formulated
4. Using the classical control theory approach [32] aided by available or specific written computer programs: (a) the performance of the basic (original) system is determined by application of one or more of the available analysis tools and/or by simulation. (b) if the performance of the original system does not meet the required specifications, compensators are added to improve the response;
5. Using the modern control theory, several approaches present themselves:

(a) optimal control techniques; [25]
(b) self – tuning control techniques; [33]
(c) vector frequency methods; [27, 28]
(d) adaptive control techniques; [34]
(e) vector space methods; [21, 22]
(f) variable structure control methods [41] sliding modes and their application in VSS.

The classical control techniques are based on trial – and – error, and depend very much on the past experience of the engineer for fast and efficient design. On the other hand, the modern method has well defined mathematical procedures. However, both techniques involve large computations. In the classical case, the early researchers in a bid to avoid the enormous computations devised approximate methods of obtaining the relevant plots. However, in the present age, those methods are considered very slow and their accuracy cannot meet the precision demands of modern technology.

POWER SYSTEM CONTROL

Power system control is a sub-field of Power Engineering that deals with the deployment of control theory to the solution of control problems in power systems. Traditionally two parameters characterise the dynamics of a typical power system, namely voltage and frequency. It follows that the problem of controlling the dynamics of a power system can be separated into two major loops: The Megavar-Voltage Control problem and the Megawatt-Frequency control problem. While the former control reactive power injection/absorption so as to maintain the voltage at its rated value, the latter controls real power generation and consumption so as to regulate the frequency at its nominal value, which is conventionally called Automatic Generation Control (AGC). As power systems become large and more complex coupled with advances in power electronics research, it becomes necessary to introduce new control devices for the management of line ampacity, power transfer capacity etc. This has given rise to Flexible AC Transmission Systems (FACTS) and Unified Power Flow Controllers (UPFC). Suffice it to say that in recent times, the power system has become a test for diverse robust control algorithms.

POWER SYSTEM AUTOMATION

Automation is the use of control systems and Information Technology to reduce the need for human work in the production of goods and services [1]. In the particular case of power systems, full automation has been deployed to areas like sub-stations, control centres, dispatch centres, generating stations etc. Further advances in power industry automation has given rise to smart metering and smart grid systems where the distribution network including tariff collections functions appropriately with minimal human intervention. It must be stated here that the success of any power market liberation depends heavily on the level of automation. Some automation tools are Human – Machine – Interface (HMI), Artificial Neural

Networks (ANN), Distributed Control Systems (DCS), Supervisory Control and Data Acquisition (SCADA) systems, Remote Terminal Units (RTUs) etc.

RESEARCH CONTRIBUTIONS

Contemporary trends in research execution is towards inter-disciplinary collaboration. Therefore, in my research career, I have collaborated with local and foreign colleagues as clearly shown in the list of publications. In most of these efforts, my contribution has been to place my modest expertise in **Control Systems Engineering** at the disposal of the group, leading to improved design algorithms in terms of efficiency maximization and / or minimal expenditure of control energy.

Specifically, in the field of **Power System control,** we had deployed Sliding Mode Control theory to develop improved algorithms for LFC design. It was possible to develop models of the Nigerian Power System which are receptive to application of modern control theory to various control problems inherent in power system operations and planning. With the emergence of restructuring in the Electricity Supply Industry (ESI), we also expanded the traditional LFC burden to include the implementation of bilateral contracts in a deregulated power network. We also developed models for predicting investment time and location in a typical Wholesale Electricity Market (WEM).

Our work on **Renewable Energy Technologies** centers around the **Doubly-fed Induction Generator (DFIG)** for wind energy conversion and small hydropower stations (SHS). Our effort has developed the "fully controlled" scheme, which is unique in providing two additional degrees of freedom of control. In practical terms, it widens the operating speed range by decreasing the "stalling" speed and increasing the "furling" speed. It holds great promise for rural electrification in remote communities where grid connection is economically unviable. Furthermore, our work on the deployment of Stand Alone Photovoltaic Systems has shown that the introduction of the fourth leg to a typically 3-leg inverter improves fault tolerance and overall network stability.

In the area of **Engineering Education,** our focus has been to develop tools for teaching and research. Our results have found great application in Control Systems Engineering and Computer Aided Design.

Power Quality Assessment (PQ) has become an important issue in today's world. We have been able to characterise different PQ stressors to the Nigerian grid and distribution networks with massive support from PHCN. Next stage is to identify signatures of various sources of PQ distortions with a view to apportioning responsibilities and imposing penalties.

Finally, in a world full of radiators and absorbers at every nook and cranny, the field of **Electromagnetic Compatibility (EM)** has assumed a prominent position. Our main focus is analysis of EM interference on typical installations from lightning and switching sources as well as quantification of shielding effectiveness of materials in different media and under various excitation signals. We are just starting, but our Polish and UK collaborators have shown tremendous zeal. Ph.D. students have been admitted, so, the vision is clear and the horizon wide.

Mr Vice-Chancellor sir, in our area of endeavour, research efforts are not regarded as complete until the developed systems are practically deployed. In other words the above mentioned research directions are on-going and will continue till years to come. However, permit me to quickly describe our modest achievements in these research efforts while emphasising the direction of further work to achieve a deployable system capable of improving the human condition.

A. POWER SYSTEM CONTROL

1. Automatic Generation Controller for the Nigerian Power System

Prior to 1988, the team of Frank N. Okafor, James Katende and C.O.A. Awosope had developed Computer Aided Control System Design (CACSD) tools for Single Input Single Output

(SISO) control systems which was later extended to Multi Input Multi Output (MIMO) control systems. These tools were being deployed as Computer Aided Instruction (CAI) for the teaching of under-graduate and post-graduate programs in our Department [35,36].

On the basis of the above projects, the Central Research Committee (CRC) of the University of Lagos, for the first time, made money available to us through a research grant to purchase a state of the art computer- an Intel 80286 processor, for further work. The issue then was the application of the developed tools beyond the classroom. Coincidentally, the operation of the Nigerian power system at that time was fraught with frequent collapses which necessitated our investigating its control mechanism, since the available generation capacity and the transmission/distribution infrastructure were still reasonably adequate.

Mr. Vice-Chancellor sir, two parameters essentially characterise the dynamics of a typical power system viz: voltage and frequency. It follows that the problem of controlling the dynamics of a power system can be separated into two major loops: The Megavar-Voltage Control problem and the Megawatt-Frequency Control problem. While the former controls reactive power injection/absorption so as to maintain the voltage at its rated value, the latter controls real power generation and consumption so as to regulate the frequency at its nominal value which is conventionally called Automatic Generation Control (AGC) or Load Frequency Control (LFC). The AGC problem in power systems seeks to balance instantaneous real power generation with consumption so as to maintain the frequency at the nominal value (i.e, 50Hz in Nigeria). A block diagram of a typical AGC scheme is shown in fig. 1.

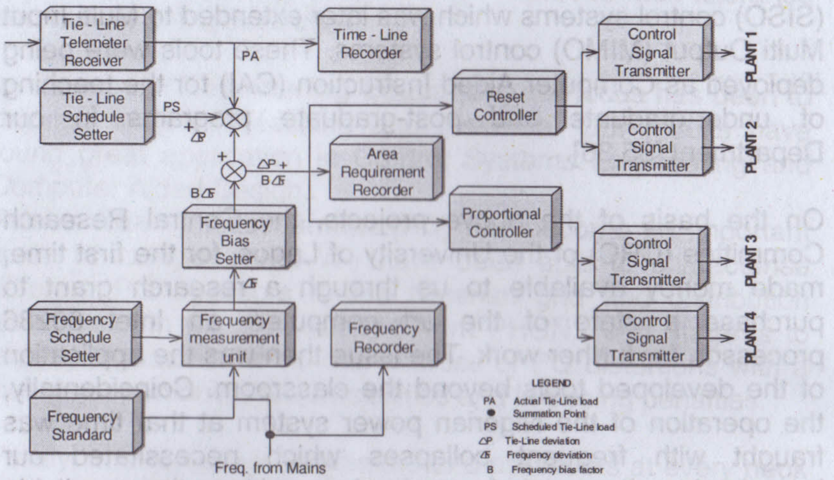

Fig.1. AGC scheme for a system with one tie – line.

Whenever the generated power is more than consumption, the frequency goes up and vice versa when power consumption is higher than generation. In each case the AGC system is expected to restore the frequency to its nominal value in a time short enough to forestall large deviations. Preliminary investigation on the Nigerian Power System at that time (1989) showed that the LFC process was and is still completely manual, relying on telephone instructions from the operators at the National Control Center (NCC) Osogbo to their counterparts at remote generating stations, through Power Line Carriers (PLCs) for necessary generation output adjustments. In recent times, Global System of Mobile telecommunications (GSM) has been introduced as a means of speeding up the transfer of NCC instructions but this rather makes matters worse due to poor network performance. Either way, this procedure introduced relatively long dead time which caused frequent instability.

It was also discovered that the system experienced large frequency deviations beyond the usual first order which is assumed in control system design. It therefore became necessary to determine whether contemporary AGC technology which was based on proportional plus integral (PI)

control action would be suitable for the Nigerian system. PI controllers suffer from reduced robustness in terms of high sensitivity to system parameter variations and low disturbance rejection capability. Meanwhile, a power system is typically a non-linear system whose parameters vary with operating conditions and which is subject to continual disturbances occasioned by changes in load demand. It was therefore, little surprise when simulation studies was used to show that the then Energy Management Systems (EMS) incorporating PI control action for AGC was not suitable for the Nigerian power system. After close to 4 years of dedicated research, I came up with a new AGC scheme which, if incorporated into present day EMS would enhance its performance during large frequency deviations. This scheme derives from the theory of Variable Structure Systems (VSS) [37-41]

A Variable Structure Control System (VSCS) belongs to a class of non-linear systems with a structure that varies according to a prescribed switching logic. By so doing, it is able to adopt a certain type of motion called the sliding mode during which it acquires invariance properties to plant parameter variations and a measure of disturbance rejection capabilities. Apart from the inherent simple structure and robustness of VSCS, its choice for AGC is further informed by the following reasons:

- the advent of new design techniques coupled with advances in electronics has greatly facilitated the practical realisation of sliding mode;
- VSC seems to be a natural way of exploiting the use of the new power electronic components which operate in the switching mode only;
- Finally, the practicability of VSCS has been amply demonstrated for a wide range of industrial plants which include amongst others; robot manipulators, metal cutting machine tools and electrical drives.

The main results of this project can be summarised as follows:-

i) A new strategy was proposed, based on the theory of variable structure systems, for the automatic generation control of electrical power systems, which will greatly improve on the performance of the presently used PI control scheme [42,43]

ii) A computer aided design tool was developed for online synthesis of the proposed variable structure automatic generation control (VSAGC) scheme on an industrial standard micro-computer (see fig.2. for structural details) [44]

iii) An AGC model of the Nigerian power system suitable for the application of modern control theory to achieve frequency regulation was developed-see fig 3.[39,40]

iv) A VSAGC scheme was designed for the Nigerian electric power system and its performance evaluated using digital computer simulation.

v) Also presented is a comparative study of the VSAGC scheme and conventional PI-AGC strategy using digital computer simulation-see fig 4. In this figure it is obvious that the performance of the Variable Structure-AGC (solid lines) is superior to its PI counterpart (dotted lines) in terms of lower overshoot and shorter settling time.

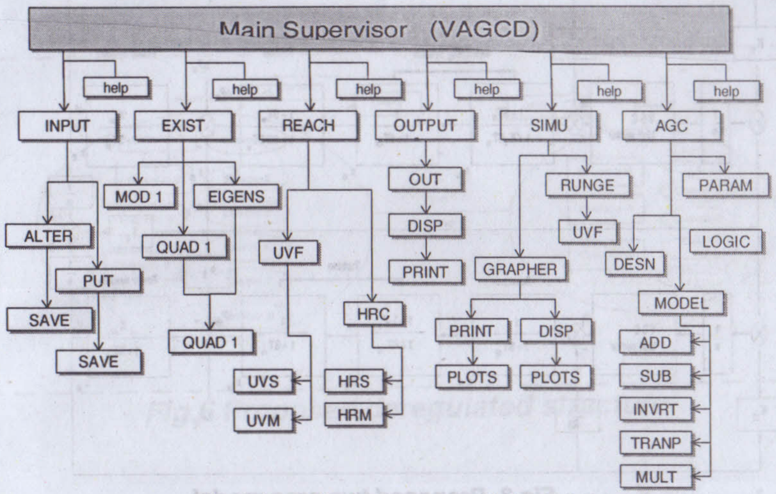

Fig.2. Detailed structure of the CAD tool

This study has developed a two-area interconnection model for the entire Nigerian power system, covering close to 900 thousand square kilometres as proposed in fig (3) [39 & 40]. Area 1 is fed from predominantly gas & oil fired thermal generating stations in the south, while Area 2 derives its power from the three hydro-generating stations along rivers Niger and Kaduna respectively. it follows therefore, that four Gencos and 6 Discos make up area 1 while area 2 contains 3 Gencos and 5 Discos as shown in fig 5. Both areas can buy or sell power to each other such that the scheduled interchange power in magnitude and direction is determined by the load forecasts of the previous day. In reality, the major load consumption centres are in the south, led by Lagos, the economic capital which consumes about 50% of the total power produced. This implies that area 1 would continuously import power from area 2. Also, the available transfer capacities of most of the lines are very low, a direct consequence of the weak grid structure and hence, the System Operator (SO) must decide how to route the power flow. The above factors which are common in developing economies tend to limit the deregulation options to what has been described as "constrained deregulation".

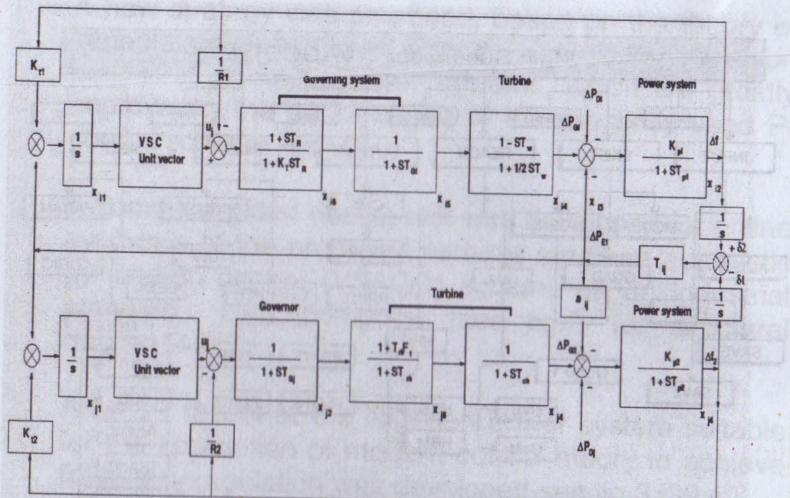

Fig.3. Proposed two area model

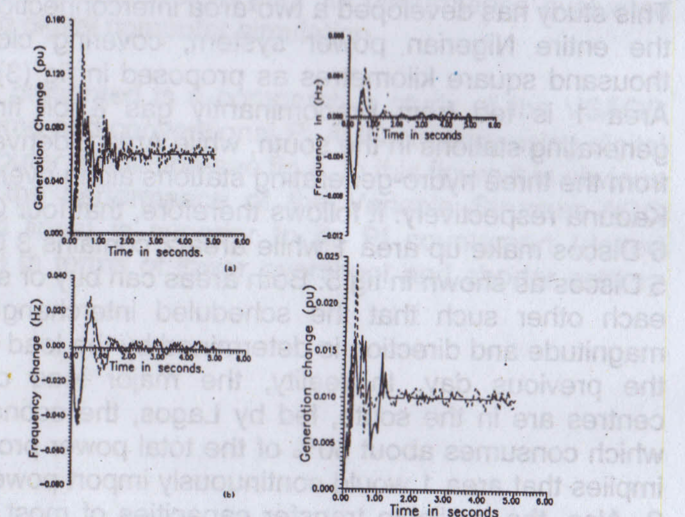

Fig.4. System responses for various changes in load demand
..............PI———— VSS

Operation of a Deregulated Nigerian Power System

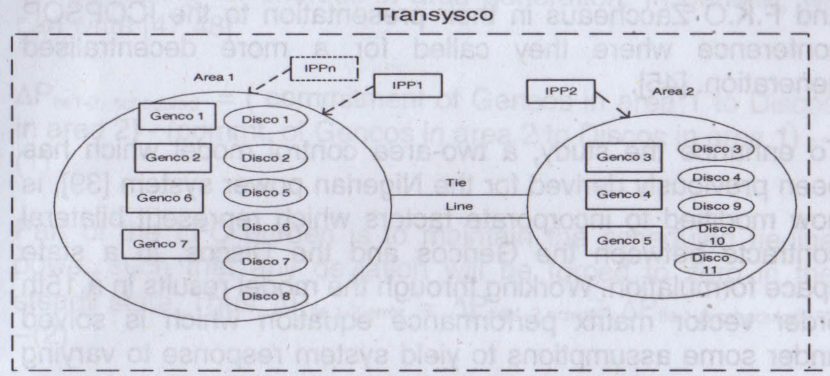

Fig.5 Proposed deregulated structure

The aim of the study is to show operating possibilities of the Nigerian power system after deregulation. It must be realised that in an automated system, it is the AGC equipment that practically realises the demands of the distribution companies (Discos) from the generating companies (Gencos). The transmission company (Transco), only one in this case, will ideally transmit the power as demanded.

It has to be understood that the proposed free market AGC does not require the measurement of actual load variations. However, the Disco demand profile should be recorded at respective injection points. This will enable the system operator to keep a tab on the liability of each Disco to inadvertent power demand over a given time. The Gencos which respond to this inadvertent power demand should also be identified through generation records over the same time. A simple balancing procedure can then match the creditors with the debtors.

However, the ability of the Transco to satisfy the actual demands of the Discos in terms of quantity and source will depend on the ampacity of the available lines. Hence, the optimal power flow problem must be solved first before the

Transco can guarantee a firm contract between a Disco and a given Genco. This problem has been foreseen by F.A.Somolu and F.K.O Zaccheaus in their presentation to the ICOPSOP conference where they called for a more decentralised generation. [45].

To enhance the study, a two-area control model which has been previously derived for the Nigerian power system [39], is now modified to incorporate factors which represent bilateral contracts between the Gencos and the Discos, in a state space formulation. Working through the model results in a 15th order vector matrix performance equation which is solved under some assumptions to yield system response to varying contract conditions. In this way, the physical constraints on system operation can be better appreciated as well as some necessary conditions for efficient system performance.

Assuming a two area interconnection (fig.5), the block diagram of fig.6. depicts the demand flow directions by Discos in one area from Gencos in the same and alternate areas. Details can be obtained from [46] Suffice it to say that the solution involves analysing a 15x15 matrix part of whose elements are functions representing the AGC set points. In line with the procedure employed in [48], the block diagram of fig.2, it represents LFC implementation in a free market environment. In our case, two representative Kaplan units in area 1 and two gas units in area 2 are used for LFC. Like in the traditional two-area model, all the area demand must be met by their own area generation plus the scheduled tie-line power. Thus, any change in load demand of the Discos in one area is treated as a local change in load represented by ΔP_{Li} and added at the input of the power system block. The unit commitment factor uc_{ij} is a measure of what part of the total generation of Genco j is allocated to Disco i by the Transco. The actual values are solely determined by the Transco as explained earlier. Monitoring the uc values will help the Transco to compute the cost of inadvertent load demands and the liability of the respective Discos.

Note that the direction of scheduled tie-line power is aimed at compensating for shortfall in area generation. In general, we can write [47,48]:

$\Delta P_{tie1\text{-}2,\ scheduled}$ = (commitment of Gencos in area 1 to Discos in area 2) - (commt. of Gencos in area 2 to Discos in area 1) --- (1)

Part of the LFC burden is to maintain the scheduled tie-line power such that any deviation will be forced to zero in the steady state. Thus, $\Delta P_{tie,1\text{-}2,error} = \Delta P_{tie,1\text{-}2\ actual} - \Delta P_{tie,1\text{-}2,scheduled}$ ---(2)

must be made to vanish by LFC action. The control signal which actuates change in generation, otherwise called area control error (ACE) is then defined for each area as:

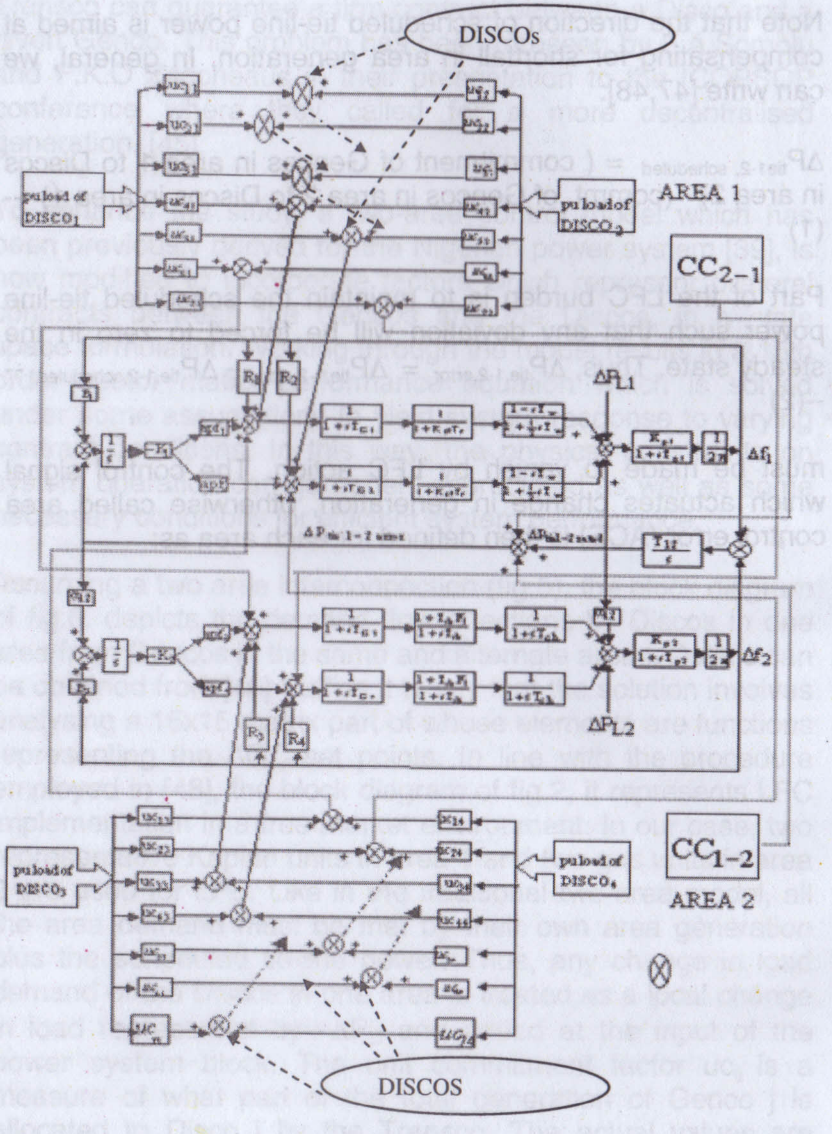

Fig.6. Proposed operation of a deregulated Nigerian power system (uc – unit commitment)

$ACE_1 = B_1\Delta f_1 + \Delta P_{tie1\text{-}2,\ error}$ ---(3a) $ACE_2 = B_2\Delta f_2 + \Delta P_{tie2\text{-}1,\ error}$-(3b)

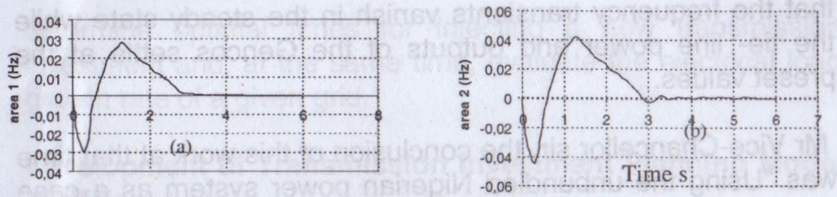

Fig. 5(a,b) Frequency transient against time in seconds

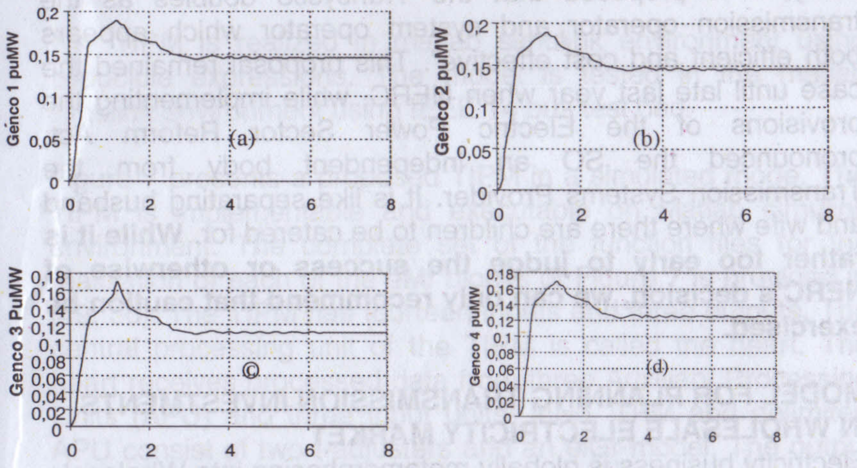

Fig. 6(a,b,c,d) Transients of Genco outputs against time in seconds

Where B is the frequency bias setting (in MW/0.1 Hz, a negative value) and f is frequency:

State Space Representation

The LFC scheme depicted in fig.6 can be analytically expressed in the usual state variable equation in closed loop as:

$$\dot{X} = AX + BU \quad \text{-------------(4)}$$

where the state vector $X \varepsilon \Re^{n}$; the input vector $U \varepsilon \Re^{m}$; while $A \varepsilon \Re^{nxn}$ and $B \varepsilon \Re^{nxm}$ are the system and input matrices which can be extracted from fig.6 by the standard technique.

Figs. 5(a & b) show the response of the area frequencies while 6(a, b, c & d), depict the excursions of Genco outputs respectively in response to demand signals from the System Operator (SO) to change generation set points. It is seen that the frequency transients vanish in the steady state while the tie- line power and outputs of the Gencos settle at the preset values.

Mr Vice-Chancellor sir, the conclusion of this work at that time was "Using the unbundled Nigerian power system as a case study, it is proposed that the Transysco doubles as the transmission operator and system operator which appears both efficient and cost effective". This proposal remained the case until late last year when NERC, while implementing the provisions of the Electric Power Sector Reform Act, pronounced the SO an independent body from the Transmission Systems Provider. It is like separating husband and wife where there are children to be catered for. **While it is rather too early to judge the success or otherwise of NERC's decision, we can only recommend that caution be exercised.**

B. MODEL FOR PLANNING TRANSMISSION INVESTMENTS IN WHOLESALE ELECTRICITY MARKET

Electricity business is globally metamorphosing into Wholesale Electricity Market (WEM), where market participants (MPs) trade in electricity. This engenders competition among MPs, thus imposing a great burden on the transmission network which, in consequence, may be operated in the way not originally envisioned. In order to allow healthy competitions among MPs and, at the same time, ensure security, reliability and availability of the grid, especially in a developing economy, there is the need for continued injection of new transmission investments into an existing grid.

Injecting a new transmission investment requires proper technical planning, which includes identifying devices to be invested on; locating an optimal place to inject a new investment, predicting an optimal time for the injection of new investment, and periodic evaluation of electrical load growth rate. These planning activities require sound models to carry them out. In that regard, we developed a Transmission Investment Planning Model (TIPM), which can be used to

determine optimal times for injecting a new transmission investment and, at the same time, evaluate the electrical load growth rate of a given grid.

Development of Transmission Investment Planning Model (TIPM):

The TIPM is realized in matlab simulink environment using deducible expressions. The model is tested in the matlab simulink environment using IEEE 14 bus test bed.

Figure 7 presents a proposed TIPM in a simulated mode. The TIPM is implementable and executable on Matlab simulink environment. The complete set of the function files for the realization of each of the eMf blocks of Figure 7 is provided in [49, 50]. The TIPM has fourteen inputs and three outputs. The central processing unit of the TIPM is called the heart. The heart receives processed data from three Auxiliary Processing Units (APU) and three input units- InNo, TRM and delimiter. APU consist of two t-adjusters and an elGr model. The output of a subsystem named elGr model is connected to the *k* input of the heart of the TIPM. To use the model, the user supplies the data required for all the transmission paths of the grid through the input units of the model, and the outputs are displayed by the model after clicking on ***start simulation***.

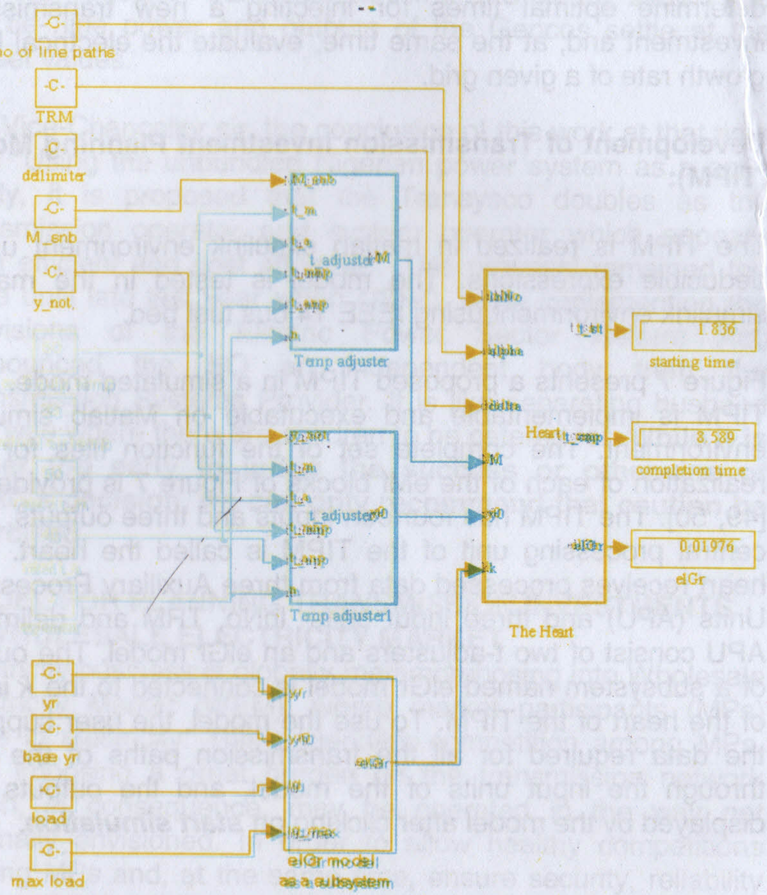

Figure 7 The Transmission Investment Planning Model (TIPM)

The research on the development of the TIPM has revealed that the concept of Available Transfer Capability of various sections of a grid connected network can be used to develop Transmission Investment Planning Model. Until now, researchers have primarily concerned themselves with finding appropriate method for computing Available Transfer Capability of different transmission paths of a grid connected network. In our work, the dynamics of Available Transfer Capability, in response to increase in electrical load [51, 52], has been used to develop a simple model that predicts the

optimal times when new investments are due in a WEM process.

Development of an electrical load growth rate model

One of the input signals to the heart of the TIPM is electrical load growth rate model (elGr) of each of the transmission paths of the grid. In that regards, Salawu, Okafor & Adetona [53] developed an elGr model using concepts based on the theory of growth function.

The algorithm developed for the implementation of elGr model is presented in the form of a flowchart in figure 8. The flowchart is coded using embedded functions (eMf) and math blocks in the matlab simulink environment. figure 3.0 shows the elGr model, developed from figure 8. The complete set of the function files for the realization of each of the eMf blocks, (Adetona (2010)) [56]. A close observation of figure 3.0 reveals that it has four input terminals for data. For the elGr to be determined using the proposed model, the necessary data are fed into the four input terminals of the model. The $R^2$and m_g of each of linear, exponential and power blocks are displayed accordingly. The auto-switch block connects the m_g of the block whose $R^2 \approx 1$, and highest to the model processor and for onward display as elGr after processing. The connection to the output display via model processor is automatic. It was built in matlab simulink environment. The model is tested as a stand-alone model, validated with appropriate data, and found to be okay. The model can be utilized by Market Operators (MOs) and MPs in the WEM process as a stand-alone model

The research on the development of an electrical load growth rate model has demonstrated how the theory of growth functions can be applied to developing an effective model that determines the rate at which electrical load grows in a given WEM. All the while, the practice has been the use of either exponential or linear growth functions to develop a model, which can be used to evaluate the rate at which electrical load grows in an electricity market. However, this research devised a system of combining the linear, exponential and power growth functions, and of identifying the appropriate one among them.

Development of a new algorithm for realizing wireless MVA meter

In the course of building TIPM and elGr model, it is realized that MPs need to capture the total power (MVA) flowing through the transmission path of interest without necessarily having access to Transmission Service Provider (TSP) facilities. To that effect, we developed a new algorithm for realizing offline MVA meter (Adetona et al, 2011) [55]. The new algorithm is developed using the Hall Effect Field principle.

The algorithms used to implement transmission line and wireless MVA meter models are presented in figures 9 and 10. In the study, the wireless MVA meter is simulated in Matlab 7.5 simulink environment. The simulink model of the balanced transmission circuit and wireless MVA meter is depicted in figure 6.0. The embedded Matlab function and math blocks are used to model the transmission line and components of the wireless MVA meter. The complete set of the function files for the realization of each of the eMf blocks of figure 9 is provided in Adetona (2010) [56].

Our work on the development of a new algorithm for realizing wireless MVA meter has expanded the literature in that respect being the first to demonstrate how Hall Effect Field principle can be used to develop a sound algorithm for realizing wireless MVA meter. Before now, to build an appropriate algorithm for realizing wireless MVA meter, research activities were focused on the use of magnetic coil that is based on Faraday's law of electromagnetic induction. However, in our study, the new algorithm developed and simulated in simulink environment is based on Hall Effect Field principle.

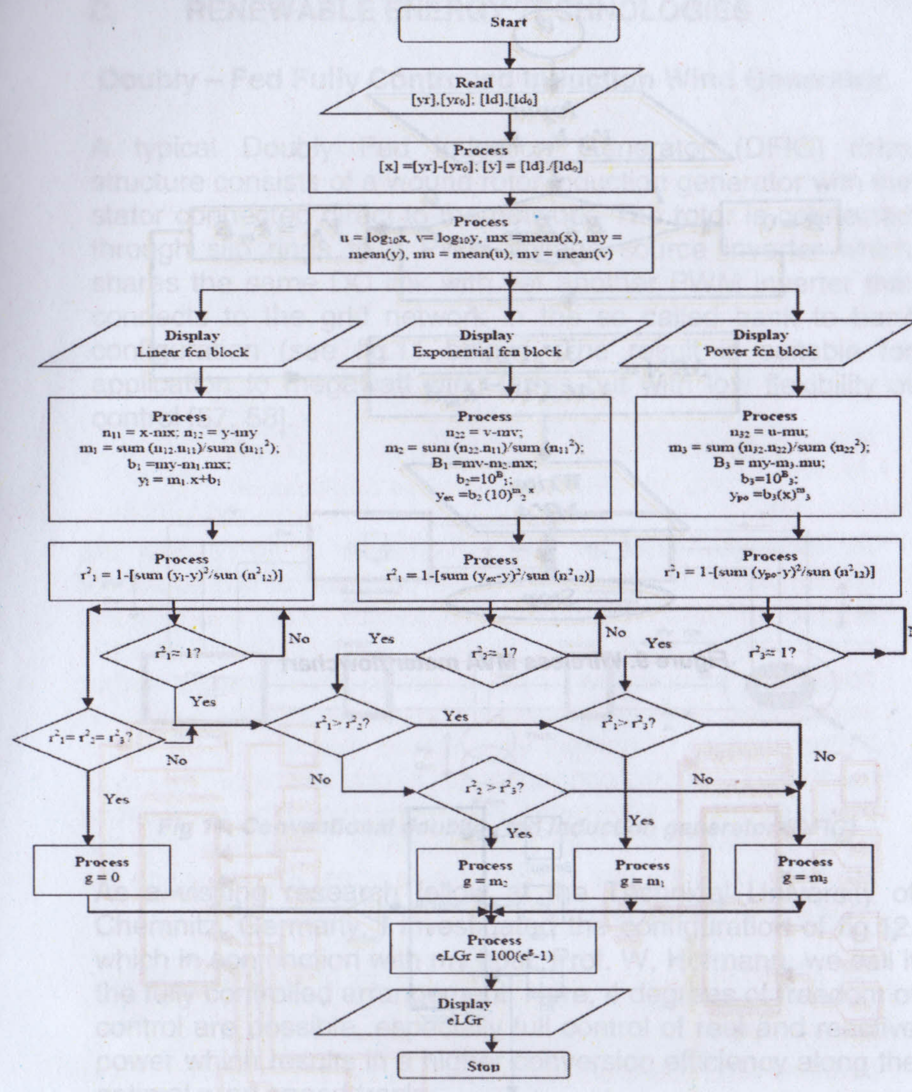

Figure 8. An elGr model flowchart

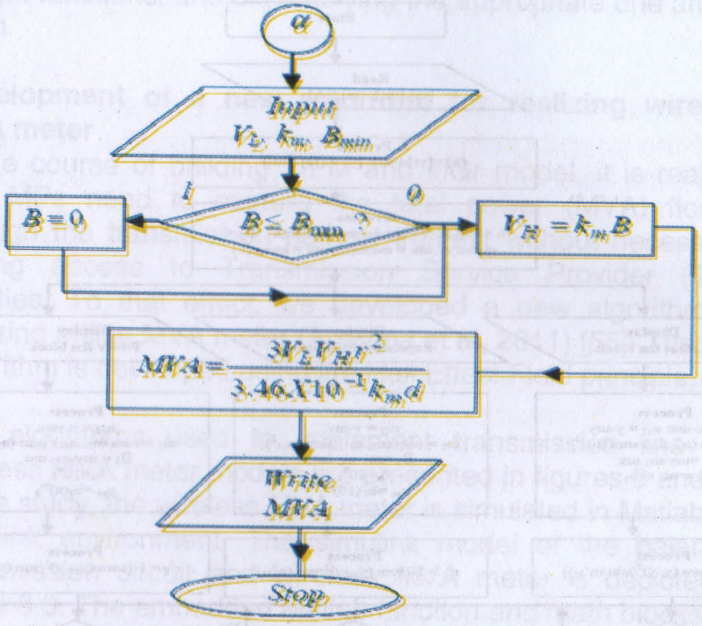

Figure 9. Wireless MVA meter flowchart

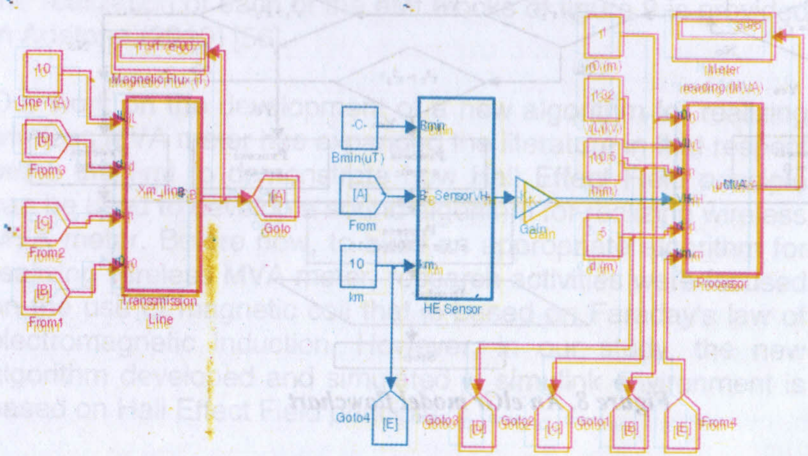

Figure 10. The simulink model of the transmission circuit and a wireless MVA meter

C. RENEWABLE ENERGY TECHNOLOGIES

Doubly – Fed Fully Controlled Induction Wind Generator

A typical Doubly Fed Induction Generator (DFIG) drive structure consists of a wound rotor induction generator with the stator connected direct to the network. The rotor is connected through slip rings to a PWM voltage source inverter which shares the same DC link with yet another PWM inverter that connects to the grid network in the so called back to back configuration (see fig.11 below). The result is suitable for application to megawatt wind farms but with low flexibility of control [57, 58].

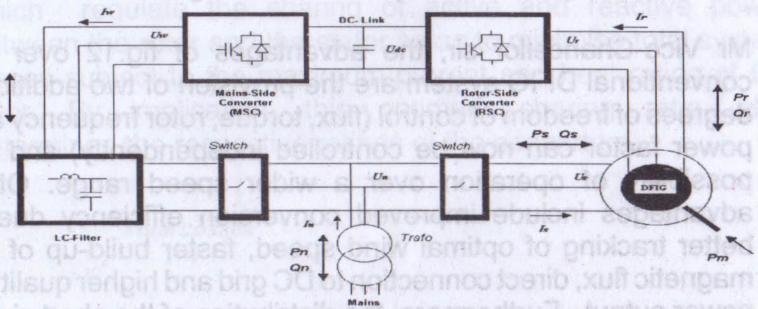

Fig 11. Conventional doubly – fed induction generator (DFIG)

As a visiting research fellow at the Technical University of Chemnitz, Germany, I investigated the configuration of fig.12. which in conjunction with my host, Prof. W. Hofmann, we call it the fully controlled arrangement. Here, 4 degrees of freedom of control are possible, especially full control of real and reactive power which results in a higher conversion efficiency along the optimal wind speed track.

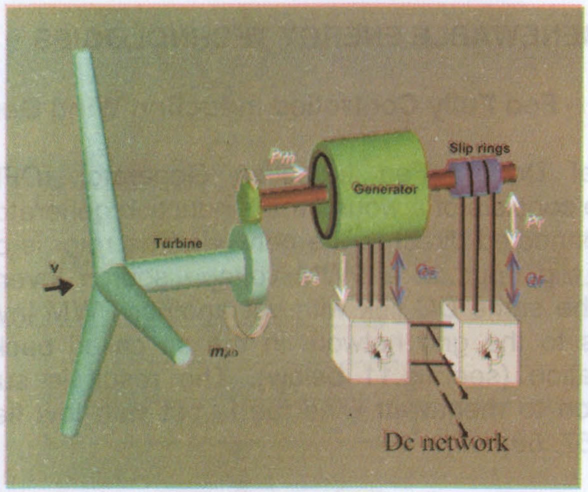

Fig.12. DFIG fully controlled configuration

Mr Vice-Chancellor sir, the advantages of fig.12 over the conventional DFIG system are the provision of two additional degrees of freedom of control (flux, torque, rotor frequency and power factor can now be controlled independently) and the possibility of operation over a wider speed range. Other advantages include improved conversion efficiency due to better tracking of optimal wind speed, faster build-up of the magnetic flux, direct connection to DC grid and higher quality of power output . Furthermore, the distribution of the short circuit current between the rotor and stator side converters and the ability to force the flux to zero at a very fast rate enhance the reliability of the system under faulty conditions.

For supply to AC systems, the frequency of supply to the load is decoupled from the frequency of generation which makes it suitable for high performance applications. Furthermore, in offshore wind powered generating systems, the configuration of fig.12 with the main side converters placed on-shore, offers an interesting solution to the high capacity behaviour of 3-phase energy transmission through underwater cable especially when supplying inductive load. However, these advantages are at the expense of increased financial cost which can be justified in quite a number of applications. Also

its application is limited by the maximum available size of converters.

Performance Objectives

The system is specified for the following characteristics:

1. both the stator and the rotor must contribute to magnetization;
2. during "sub-synchronous" operation, the rotor takes power from the DC line;
3. during "over-synchronous" operation, the rotor delivers power to the DC line;
4. high efficiency of operation.

For optimum efficiency, the losses should be minimum. It therefore follows that control schemes must be developed which regulate the sharing of active and reactive power between the rotor and the stator so as to minimise total system losses subject to the maximum current and heat rating of the rotor. By implication, this optimum sharing ratio, also determines the respective ratings of the converters.

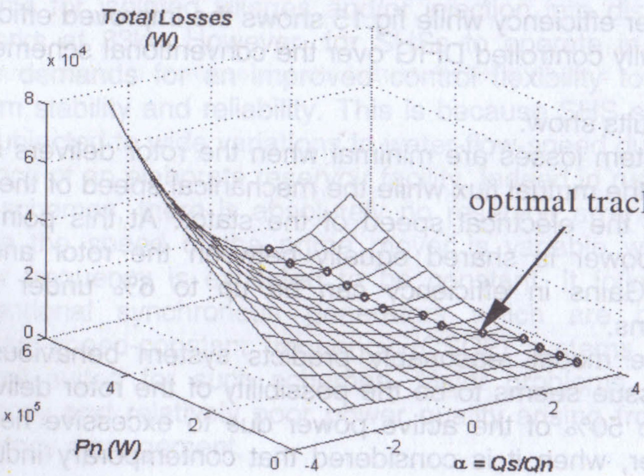

Fig.13 Trajectory of Optimal Reactive Power Splitting.

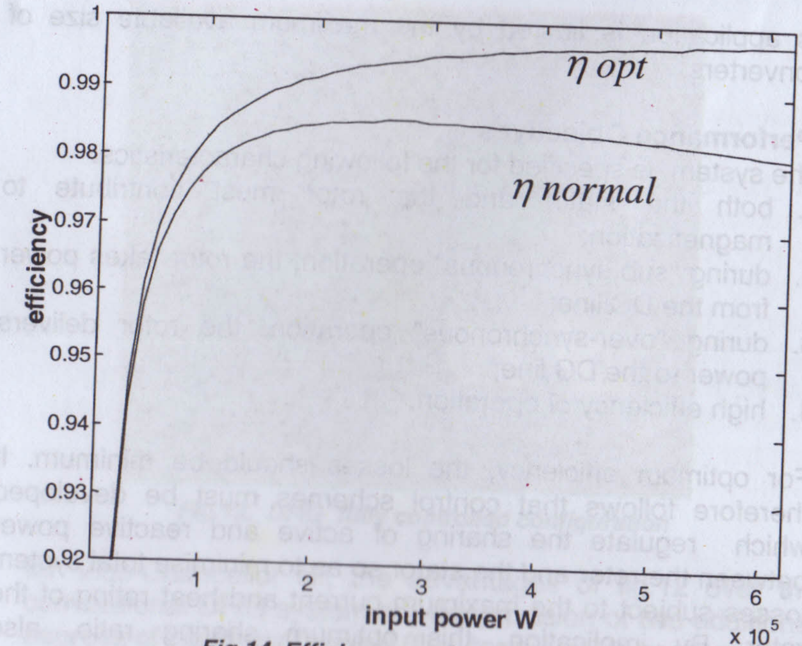

Fig.14 Efficiency against input power

Fig 14 shows the optimal track of the reactive power sharing for higher efficiency while fig.15 shows the improved efficiency of the fully controlled DFIG over the conventional scheme [59-65].

The results show:

- that system losses are minimal when the rotor delivers about 64% of the mutual flux while the mechanical speed of the rotor is twice the electrical speed of the stator. At this point. the active power is shared equally between the rotor and the stator. Gains in efficiency can be up to 6% under these conditions.
- that the model reasonably predicts system behaviour. A major issue seems to be the possibility of the rotor delivering close to 50% of the active power due to excessive heating. However, when it is considered that contemporary induction generator designs are equipped with rotor-air-cooling mechanisms, the solution to the above problem is near.

Application to Small Hydro Power Stations (SHS)

Mr Vice Chancellor sir, distinguished ladies and gentlemen, power networks of developing economies are expected to benefit most from contemporary concepts in decentralised generation to enhance reliability of supply and high voltage quality. In sub-Saharan Africa, a potential source of extra generation as one ascends from the coast of the Atlantic Ocean to the tip of the desert is small hydro generating schemes. Nigeria alone has about 300 of such potential sites but only about four are being exploited. The situation is not any better in the neighbouring countries of the West African sub-region. The reasons for low exploitation may vary slightly from country to country but are usually derived from low conversion efficiency arising from the use of inappropriate technology. The cost per kilowatt output is therefore, relatively high, which affects profitability and hence, discourages investment. It is gratifying to note that through such institutionalised framework as New Partnership for African Development (NEPAD), African countries are undergoing a policy shift towards decentralised electricity generation. In Nigeria for instance, the thrust is to encourage small scale generating units as stand-alone systems for isolated villages and/or injection into distribution networks at 33kv. However, for SHSs to operate in such a mode demands for an improved control flexibility to ensure system stability and reliability. This is because SHS schemes are subjected to wide variations in water-flow-speed due to the absence of an elaborate reservoir facility. Indeed in run-of-the-river schemes, there is absolutely no reservoir arrangement. Hence the speed of the prime mover is variable while the power frequency is expected to be constant. It follows that conventional synchronous generators which are basically constant-speed-constant frequency (CSCF) systems will not be well suited for such schemes. Major problems are low efficiency and relatively poor power quality arising from poor frequency management.

Fig. 15 Hydro Potential Sites in Nigeria (Source NEPA)
Small Scale HYDRO Potential sites (more than 300 sites, over 800MW)
Large Scale HYDRO Potential sites (more than 17 sites, over 11,000 MW)

We deployed the fully controlled DFIG for electric energy generation from Small Hydropower Stations (SHS), which Nigeria needs for her quest towards decentralised generation [66]. The results are very promising.

- Improved conversion efficiency and control flexibility
- Enhanced power quality in terms of voltage and frequency stability.

The control scheme we utilised is shown below.

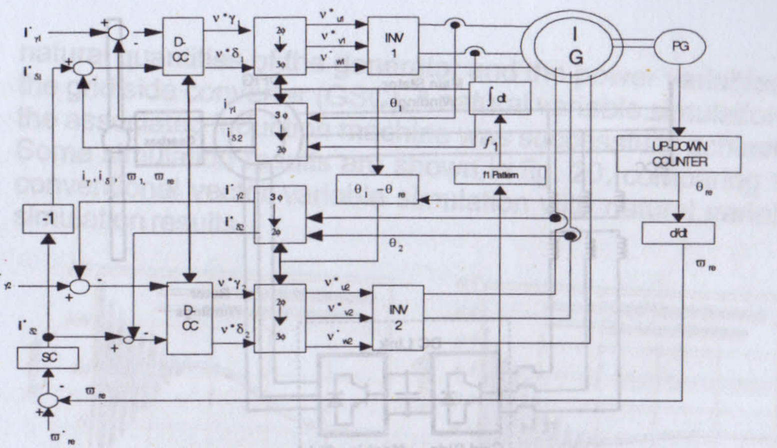

Fig. 16. Control scheme for SHS.

Extension of Conventional DFIG Capabilities

Usually, DFIGs are operated at a range not exceeding 0.3 slip above or below synchronous speed in order not to exceed the 30% rating of the converters. For operations at extended speed range beyond 0.3 slip above synchronous speed the DFIG will have to be operated in the field weakening zone. However, in that case an over-sized converter of above 30% machine rating is required because of increased power flow through the rotor.

Therefore, the research was focused on the development of two innovative topologies of induction generators and introduction of new control strategies for improved efficiency. The two network topologies are conventional doubly–fed induction generator (DFIG) topology and shorted stator induction generator (IG) topology. The conventional DFIG is suitable for sub-synchronous speed and super-synchronous speed operations while the shorted stator induction generator (IG) is applicable for low wind speed power application. Figs. 18 and 19 show the DFIG and the shorted stator IG respectively.

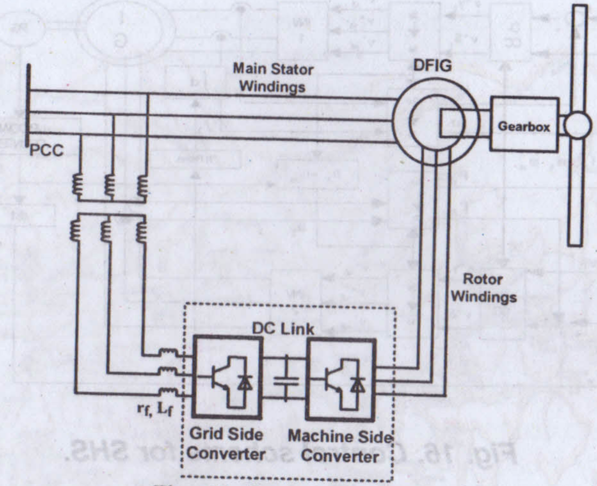

Fig. 17. Conventional DFIG

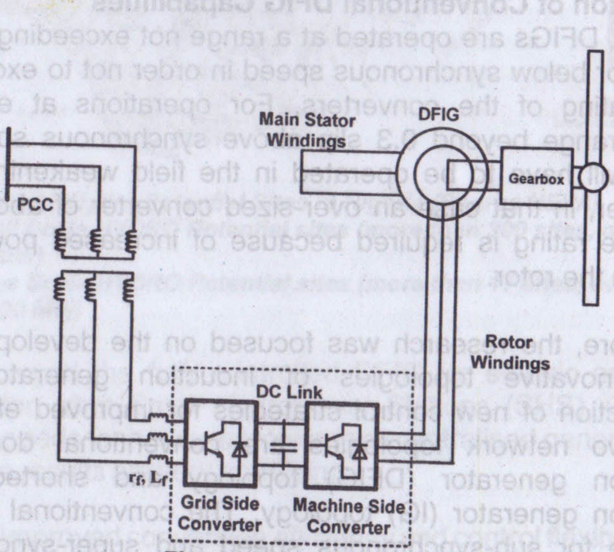

Fig. 18. Shorted stator IG

Development of a coordinate independent model of doubly-fed induction generator (DFIG)

During the course of the research, a coordinate independent analytical model of doubly – fed induction generator (DFIG) was developed. The model was obtained in terms of the natural quantities of the generator and the power variables of the grid side converter (GSC). A natural variable simulation of the associated induction machine was successfully achieved. Some simulation results are shown in fig. 20, comparing the conventional vector variable simulation with natural variable simulation results.

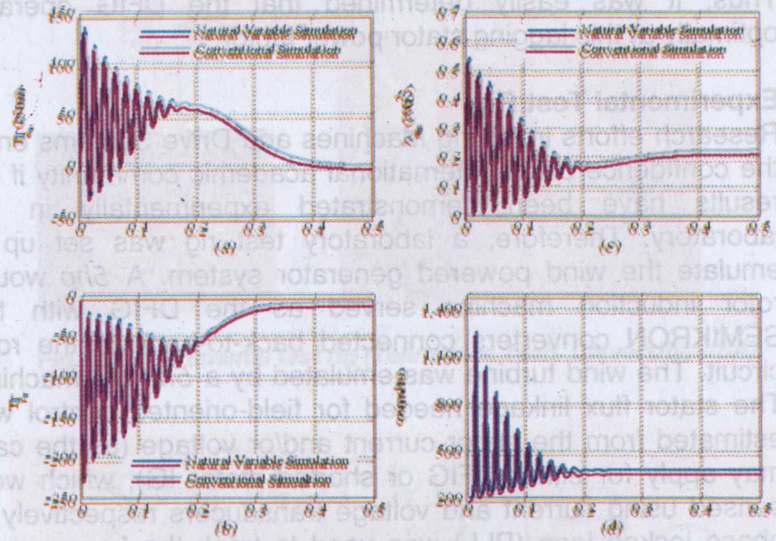

Fig. 19 (a) No load transient of electromagnetic torque for balanced stator voltage (b) No load transient of reactive torque for balanced stator voltage (c) No load transient of stator flux linkage magnitude square for balanced stator voltage (d) No load transient of stator electrical speed for balanced stator voltage

Uniquely Determining the Optimal Stator Angular Frequency

The optimal stator frequency for shorted stator induction generator (IG) was uniquely determined in terms of the machine parameters [68]. Operating at such a low stator frequency maintains a minimal loss profile than at higher frequency because at higher stator frequency, the stator current increased, and invariably the rotor current too which implied a much higher loss regime.

Determination of Optimal Stator Power Factor

An optimization procedure that uses natural and power variables was developed for estimating the optimal stator power factor of the DFIG [69]. The stator reactive power that corresponded to minimal loss was then uniquely obtained in terms of the generator's parameters and the stator flux linkage. Thus, it was easily determined that the DFIG operated optimally at this lagging stator power factor.

Experimental Test Rig

Research efforts involving Machines and Drive Systems enjoy the confidence of the international academic community if the results have been demonstrated experimentally in the laboratory. Therefore, a laboratory test rig was set up to emulate the wind powered generator system. A *5hp* wound rotor induction machine served as the DFIG with two SEMIKRON converters connected back-to-back to the rotor circuit. The wind turbine was emulated by a *5hp* DC machine. The stator flux linkage needed for field-oriented control was estimated from the stator current and/or voltage (as the case may apply for either DFIG or shorted stator IG), which were sensed using current and voltage transducers respectively. A phase locked loop (PLL) was used to track the frequency of the utility grid for effective synchronization, and another PLL was used to read the precise angle of transformation which corresponds to the stator flux orientation. The test rig is shown in fig. 20. The control schemes deployed on the machine are illustrated in figs. 21.

Fig. 22 shows the regulation of the stator flux linkage for the shorted stator IG. In the results, it is shown that the actual flux linkage follows the reference command flux linkage. In fig. 23 the reactive power of the grid side converter (GSC) is regulated to be zero so that the GSC operates at unity power factor at all time.

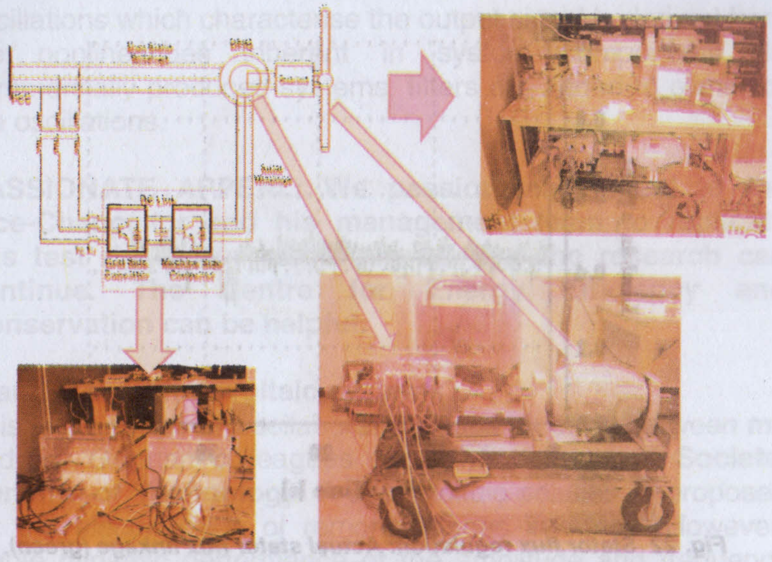

Fig. 20 Experimental test rig (Tennessee Tech. University, USA)

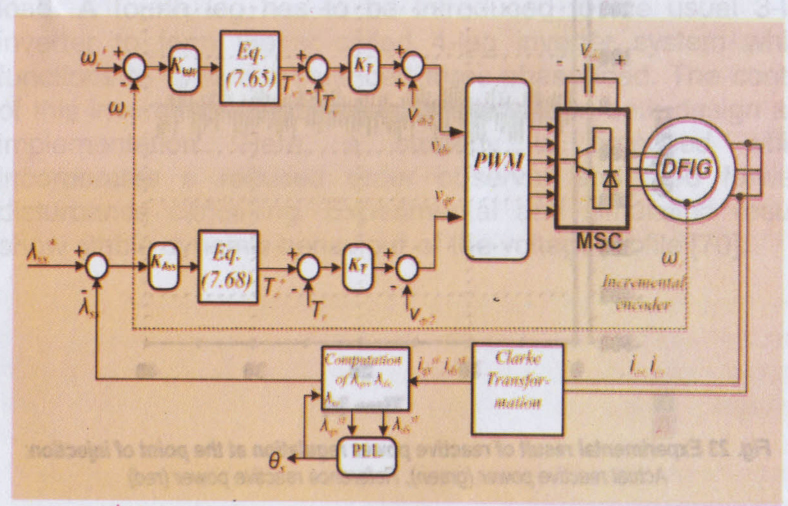

Fig. 21 Direct scalar control of MSC optimal stator flux control

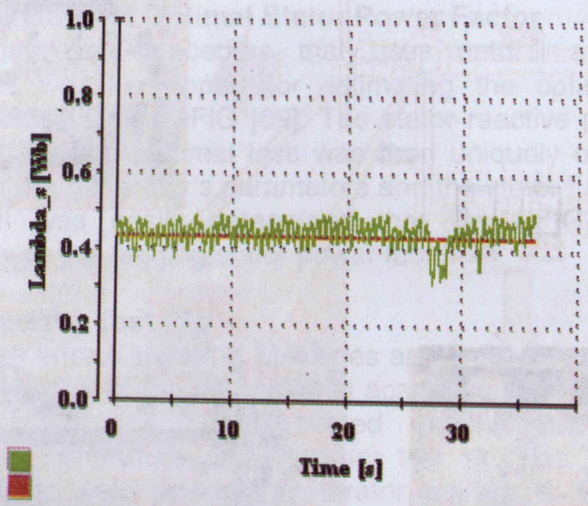

Fig. 22 Stator flux regulation: Actual stator flux linkage (green), reference stator flux linkage (red)

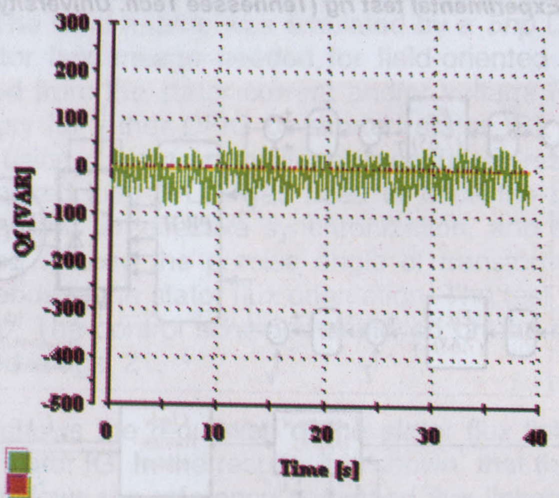

Fig. 23 Experimental result of reactive power regulation at the point of injection: Actual reactive power (green), Reference reactive power (red)

Mr Vice-Chancellor sir, the success of a control system is the ability to force the output to track the input signal. In the two experimental results shown above, the outputs followed the reference inputs, on the average. The low amplitude

oscillations which characterise the output signal is derived from the nonlinearities inherent in system components. In commercially produced systems, filters are added to eliminate the oscillations.

PASSIONATE APPEAL: We passionately appeal to the Vice-Chancellor and his management team to replicate this test rig in our laboratory so that the research can continue. The Centre for Energy Efficiency and Conservation can be helpful.

Stand-alone Photovoltaic systems

This is the result of a collaborative research effort between me and my German colleagues on **Enhancement of Societal Benefits of Technology**. A photovoltaic solution is proposed for the electrification of remote villages in Africa. However, stable dynamic performance of the amplitude and frequency profiles of the output voltage is critical to efficient operation of **Stand-alone Photovoltaic Systems** feeding a three-phase load. A fourth leg has to be introduced to the usual 3-leg inverter to form the so-called 4-leg inverter system which functions to ensure a balanced three-phase load. The control of this inverter presents severe challenges in both design and implementation. Here, a strategy is proposed which incorporates a reduced order observer and feed forward disturbance cancelling. Experimental and simulation results show stable dynamic behaviour of the voltage profile [70].

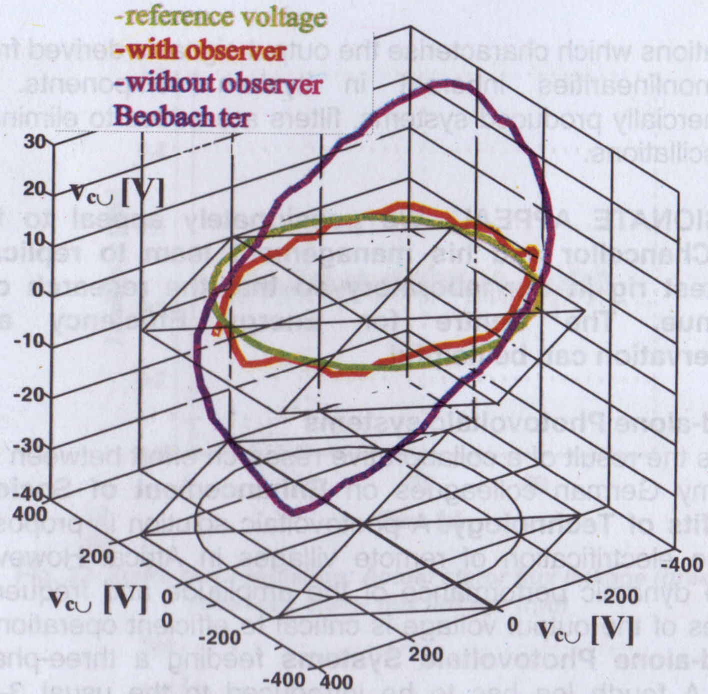

Fig. 24 3D representation of the measured output with and without observer with ohmic load of 5A

Figure 24 shows the trajectory of the reference and the output voltage with and without observer in the 3D space using the - coordinate transformation. In both cases a single phase ohmic load of 5A was applied.

Mr. Vice-Chancellor sir, both experimental and simulation results have been deployed to show the emergence of stable system with about 16% higher utilization of the DC link voltage.

Also, with head wave eliminated for load current measurement, the resulting system which is implemented on a microcontroller has been found to be cheaper, simpler and more efficient than the existing ones.

D. INTEGRATION AND EVACUATION STUDY FOR NATIONAL INTEGRATED POWER PROJECTS

Background

For about two decades, there had been no significant addition to the available generation on the PHCN (erstwhile NEPA – National Electric Power Authority) system. Nor was there any appreciable expansion of the transmission network. The result is acute power shortages and a radial, fragile Grid.

This rather dismal scenario changed in 2004 when the Federal Government commenced a massive expansion of the Nigerian electricity industry with the construction of four power stations designed to add about 1,494 MW to the Grid in the first phase (2007) and an additional 2,148 MW in the second phase (2008). The Government followed this up with the construction of seven power stations in the Niger Delta, which will add another 2,599 MW in 2007.

The total available generation by the end of 2007 is anticipated to exceed 10,000 MW – about *double* of the current available capacity. Perhaps the magnitude of the national Integrated Power Project (NIPP) is better appreciated if one considers the fact that the country's entire generation capacity, which took over forty years to develop, is being doubled in just four years. In addition, there are concurrent projects in transmission, distribution, communication and control as well as gas supply. By mid 2005, the sum total of the entire projects were brought under one corporate governance called NIPP.

Ordinarily these projects, laudable as they are, ought to have been preceded by a comprehensive study of the grid to determine the best location for the generating plants and the most efficient grid network structure. This was not done apparently due to the exigencies of the situation at that time. Realising this shortfall in the National Integrated Power Projects planning program, the then Technical committee commissioned this Integration and Evacuation study with the sole aim of determining whether the committed transmission projects can evacuate the generating plants as presently located.

Power Flow Studies

Power flow analyses were carried out under four different scenarios to evaluate resultant voltage profiles and equipment loadings given ongoing and committed NIPP projects.

The power flow analyses (carried out on only 330 kV voltage level in the interim) show that ongoing transmission projects and transmission projects under the NIPP transmission development plan can evacuate the generation capability being built or has been committed under the first phase of the NIPP (i.e. 7 NIPP Plants + Phase 1 of 4 FGN Plants). This is, however, under N-0 condition, i.e. no loss of any (critical) circuit.

ENVISAGED GENERATING STATIONS AND 330KV TRANSMISSION GRID NETWORK IN 2008 (used for the study)

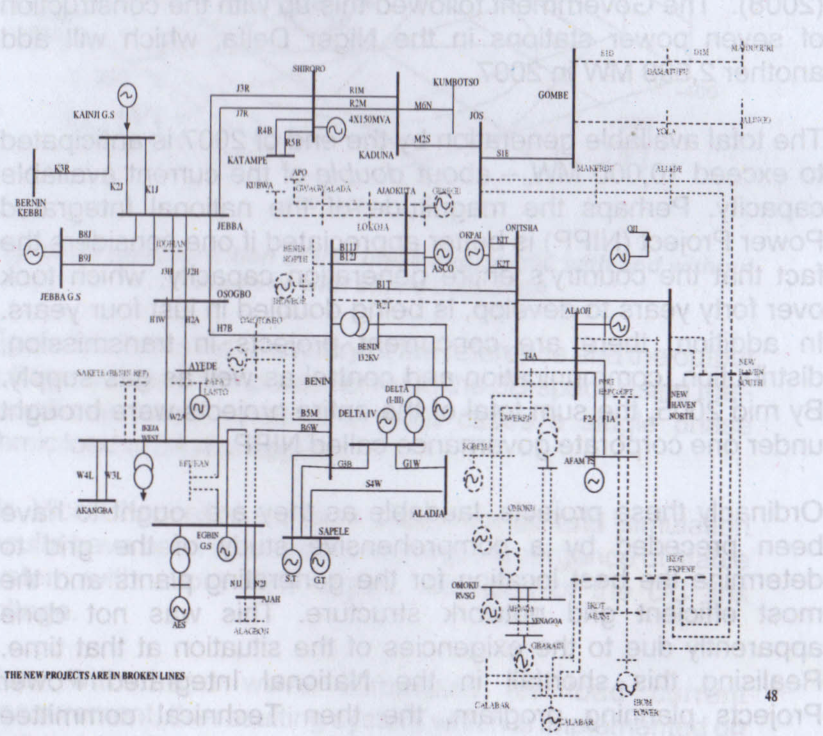

Fig. 25: Projected Nigeria Network

Also, additional transformation capacity (at 330/132 kV and 132/33 kV) as well as additional 132 kV transmission circuits

will be required, and these will be determined in follow-up studies. The voltage profile is generally good. Committed compensation schemes and operations manipulations are considered adequate to address isolated voltage issues. A major concern is possible transmission congestion in the Benin – Lagos axis and a bottleneck in Benin. The power flow study also shows that the generation capability being built or has been committed under the second phase of the NIPP cannot be evacuated even with the commissioning of ongoing or committed transmission projects.

Short Circuit Studies

Short circuit analysis was carried out to determine fault current levels at the various buses within the interconnected system, for the purpose of checking switchgear rating adequacy and for effective protective relay coordination and setting.

Short circuit studies indicate that fault levels at Benin, Alaoji, and Afam 330 kV substations – and indeed at some other substations – may exceed the rating of existing switchgear when the planned power plant and transmission development projects in the area are completed.

In the case of ongoing Alaoji Power Station project, the fault level is estimated to reach about 54 kA. This is well in excess of the 40 kA rating of switchgear already ordered.

Outline studies on the proposed Mambilla Hydroelectric Power Station show possible fault level increases of up to 16% in the NIPP area on account of Mambilla's peculiarity.

Possible measures to reduce excessive fault levels were outlined. One that is readily applied is network splitting.

Stability Studies

Transient stability may be defined as the ability of the grid / system to maintain equilibrium and re-establish itself into steady state condition, following a major disturbance (faults) on the network.

Before the start of transient stability studies, it is necessary to first simulate a case corresponding to a normal situation in a steady state power flow, and to see the ability of the system to face an incident. The power flow study will establish the initial conditions, such as busbar voltages, load (P and Q), angles, etc.

For transient stability studies, the following four variables are presented graphically to allow an easy diagnosis of the stability of the system:

Active Power: P_e, expressed in MW (electrical power)

Mechanical Power: P_m, expressed also in MW (turbine power)

Voltage at the terminal of the generators: expressed in pu

Angle (∂): it is expressed in degrees for each generator. The angle is related to the inertia centre, representing the centre of gravity of the system.

Major Findings

Products of NIPP plant can only be evacuated under N-0 condition.

Phase two of NIPP project cannot be evacuated by the current level of transmission lines investments including transformation capacity.

There appear to be low frequency oscillatory modes after faults have been cleared. It was therefore recommended that all NIPP generators be ordered with Power Systems stabilizers.

Mr. Vice-Chancellor sir, this last recommendation was quickly accepted and orders for the generators already placed were updated to include power systems stabilizers[71].

E. ELECTROMAGNETIC COMPATIBILITY

Mr. Vice-Chancellor sir, the new world order demands that functional safety both at home and the working place be taken seriously. One latent pollutant of the environment, which is neither seen nor felt by normal human senses is electromagnetic energy emitted by such equipment and installations as GSM base stations, communication masts, power substations, large electric machines to mention a few. When exposed to dangerous levels of EM energy, human tissues and vital organs can be damaged. Unfortunately, the average Nigerian is unaware of EM phenomenon and standards are yet to be set for equipment imported or manufactured in the country [72].

In contrast to other environmental pollutants, EMI is neither seen nor perceived by the usual human senses but its effects could be more damaging than the former. For instance, electromagnetic bio-effects have raised the following questions:

(a) How safe is the use of portable/mobile radio transmission close to the human body? What are the effects of communication masts including GSM base stations existing side by side with human settlement?

(b) What are the effects of non-ionising electromagnetic energy on people living near to power lines and HV work centres?

(c) What should be the minimum safety standards for people working near sources of EMI?

(d) What should be the standard step and touch voltages for such installation under lightening strike?

(e) How safe are large storage tanks of flammable fluids (petrol, gas, oil etc) under heavy electromagnetic pulse impact?.

(f) Can a GSM phone cause fire at filling stations and tank farms?

Equally of great importance is the effect of EMI on electrical and electronic systems. Electromagnetic coupling effects can cause a malfunction in sensitive electronic systems or a substantial reduction in their expected life span. In medical and military hardware, such a malfunction could have fatal consequences. It follows that there must be standards on the emission level from all equipment capable of producing EMI.

Against the above background, I initiated EMC's studies in the following areas:

Lightning Protection
Lightning protection of structures with electronic equipment or systems becomes more and more important. In the case of direct lightning strike on building or in the building vicinity the high energy impulse, which appeared, must be controlled. The old practice of having an earthed single metallic spike at the roof of a building can no more solve the earthing protection problem. Mr. Vice-Chancellor sir, a structure like the Senate building, should be subjected to modern Lighting Protection Zone (LPZ) arrangement with appropriate Surge Protective Devices (SPDs), such that overvoltages, overcurrents and impulse electromagnetic fields are limited to admissible values in any given zone.

Equipotential bonding: equipotentialization inside the equipment building is one of the means of protection that can never be called to be overestimated. The equipotentialization at the ground level concerns all the conductive installations of the site, including water pipes, sewage and central airconditioning system. More information about equipotential bonding is presented in [73].

Table 1. *Basic information about surge protective devices connected to low-voltage power distribution systems*

Designation of the SPD	Purpose of the protective measure	Place of installation	Basic electrical parameters
Type I	Protect the low-voltage power distribution system against some part of lightning current.	Main distribution board of the structure	Nominal ac voltage U_N Max. continuous ac voltage U_C Lightning impulse current I_{imp} Nominal discharge current I_N Voltage protection level U_P
Type II	Protection of low-voltage power system against voltage and current surges (L to PE, N to PE).	Sub-distribution board in structure	Nominal ac voltage U_N Max. continuous ac voltage U_C Nominal discharge current I_N Max. discharge current I_{max} Voltage protection level U_P
Type III	Surge protection against different mode surges	Socket outlets, device's terminal.	Nominal ac voltage U_N Max. continuous ac voltage U_C Nominal discharge current (L-N) I_N Nominal discharge current (L/N- PE) I_N Combined impulse (L-N) Combined impulse (L/N – PE) Voltage protection level U_P

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a.

b.

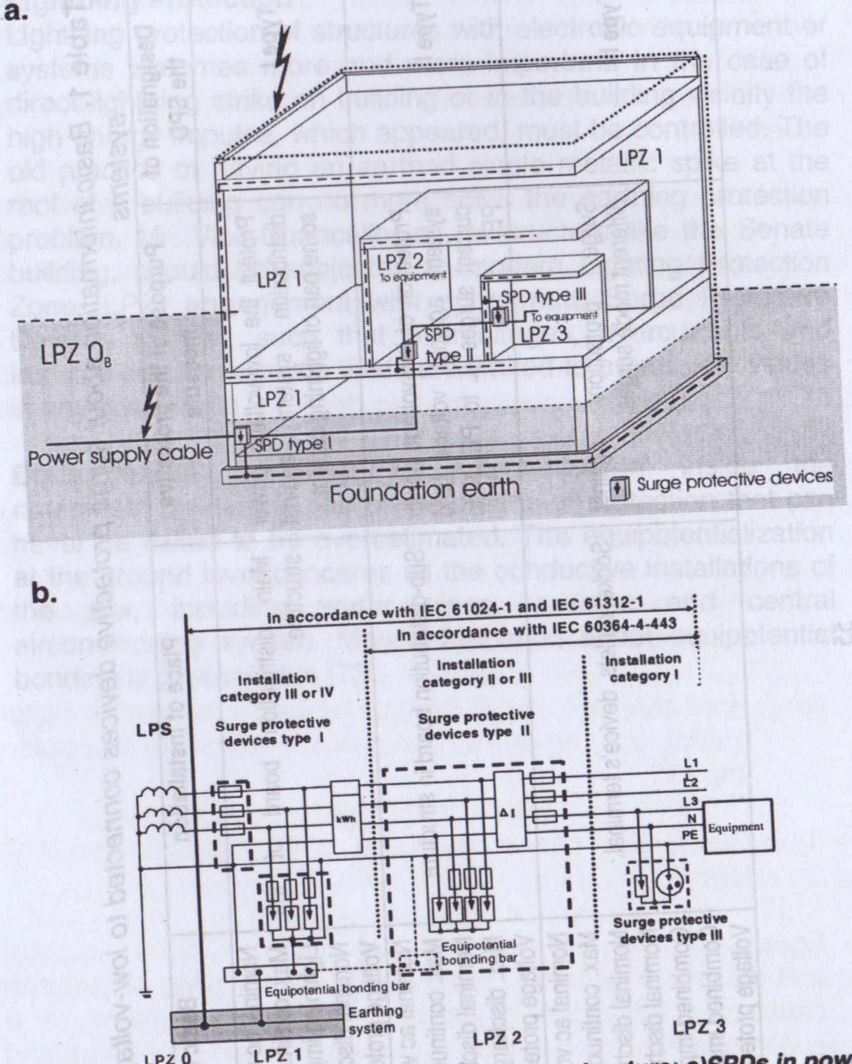


Fig.26. Three-step protection system in large structure; a)SPDs in power supply systems in large structure, b) SPDs in TN-C-S system

Lighting Electromagnetic Pulse Effects (LEMP) on GSM Base Station

The danger posed by a lightning strike on a GSM tower, to personnel and equipment within and around the base station, has attracted a lot of research interest. However, these studies and measurements have been mostly for temperate climate which render the results inappropriate for the tropics. The major aim of this paper is to conduct similar studies for a typical tropical climate with a view to highlight precautionary measures which can enhance safety of personnel and equipment [74,75,76,77].

Figure 27 shows the equivalent collection area produced by a tower of GSM station placed on a flat ground. Clearly this is a circle with a radius of three times the tower height. More information about analysis of lightning risk is presented in [77].

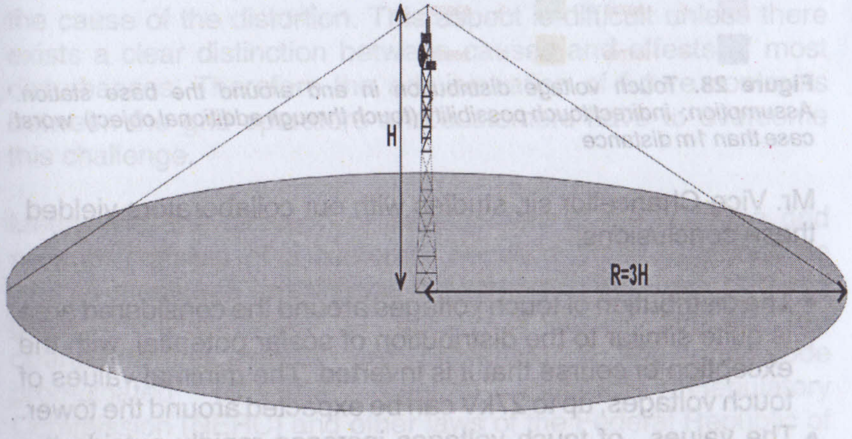


Fig. 27. Evaluation of equivalent collection area of the high tower

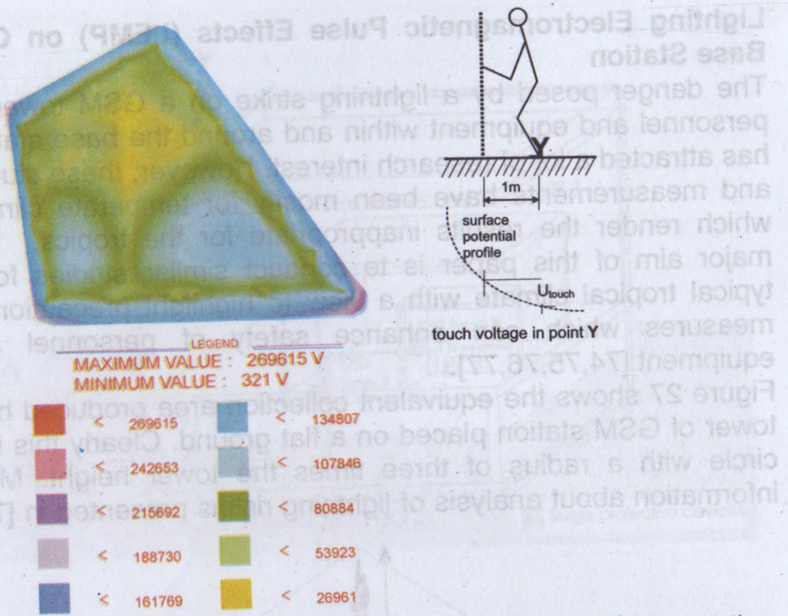


Figure 28. *Touch voltage distribution in and around the base station. Assumption: indirect touch possibility (touch through additional object) worst case than 1m distance*

Mr. Vice-Chancellor sir, studies with our collaborators yielded these conclusions:

- The distribution of touch voltages around the considered area is quite similar to the distribution of scalar potential, with the exception of course that it is inverted. The minimal values of touch voltages, up to 27kV can be expected around the tower.
- The values of touch voltages increase rapidly outside the station with increasing distance to the station fence.
- For example, up to 135 kV of touch voltage can be expected within about 2 m distance to the station fence. Close to the fence corners, this distance can be even significantly smaller as for the case of direct touching the structure..
- The maximum values of step voltages - up to 128kV can be expected around the vertical ground conductors of the station fence, especially close to the corners. Such values of step

voltages extend to about 2m diameters around the ground conductors.

- A very fast decrease of step voltages is observed outside the area enclosed by the fence. It should be pointed out that the distribution of scalar potential as well as step and touch voltages is strongly dependant on soil resistivity and the effective area for a given lightning current shape.

Power Quality Assessment

Competitive electricity market has imposed the status of "commodity" to electric power. This commodity must conform to some standards of quality for worth of its price. The major issue is how to define proper economic mechanisms capable of reasonably representing PQ technical specifications. In other words, the design of any incentive/penalty mechanism must incorporate procedures for apportioning responsibilities to the cause of the distortion. This aspect is difficult unless there exists a clear distinction between causes and effects of most disturbances. Therefore the administration of future contracts between the grid operators and customers have to overcome this challenge.

Meanwhile, the direction of development of the Nigerian grid network consists of a customer needs oriented approach as well as measures to enhance network security. Each of these goals involves issues of quality of power supply. The operational necessities are presented in the grid code promulgated by the Nigerian Electricity Regulatory Commission (NERC) and other laws of the Federal Republic of Nigeria. The general objectives include but not limited to the following:

- ❖ prescription of the permissible deviation values for PQ parameters in qualitative terms;
- ❖ defining the suppliers' responsibilities for failure to comply with these PQ parameters and customers' responsibility for emission of disturbances to the supply system;
- ❖ management of electric energy tariff by controlling rebates/discounts and compensation fees associated with PQ requirements;

❖ endowment of the grid companies and specialized firm with specified measuring instrumentation;
❖ strengthening the authority for on-line inspection of PQ factors and determining indemnity procedures and principles of conflict resolution.

Research Objectives: the emerging regulatory framework proposed by NERC for transmission and distribution business includes provisions for:

- supply continuity as a fundamental issue of quality of electricity supply service.
- voltage level and shape at PCC as a concerned issue of power quality.

Unfortunately, contemporary electricity utilization technology tends to exhibit two conflicting trends viz:

1. An increasing installation of power electronics controlled devices with high impact on perturbation level in electricity networks.
2. An increasing sensitivity of new end-user technologies to perturbation.

Against the above background, it is expected that very soon, power quality (PQ) issues will become part of end-user contracts. This implies that very soon too, PQ issues will become matters of complex legal interpretation which obviates the need for proper technical description and standardization.

The main objective of the study is to articulate all the diverse aspects of quantifying assessment criteria for power quality with a view to standardizing the requirement, for connecting customers which are potential sources of disturbances to the system. A major achievement of the study will be the development of software capable of tracking the propagation of disturbances along our radial network with a view to possibly establishing their origin.

Having enumerated the problems caused by steel plants and the need to protect public interest without compromising societal benefits, the problem to be solved by this study can be summarized as follows [78,79]:

(i) measure the power quality i.e Total Harmonic Distortion (THD), voltage unbalance, voltage fluctuation (flicker), power factor, etc. at the point of common coupling for all the steel plants and other factories connected or wishing to connect at 132KV;
(ii) examine the results and ascertain if they conform to IEC standards on power quality or IEEE 519;
(iii) study the existing standards on power quality and ascertain if they are adequate for our environment, given the relatively weak radial network;
(iv) expand the measurement horizon with a view to study the propagation pattern along our radial network of the entire harmonic spectrum and flicker event;
(v) establish a propagation model, if possible, through software development and customize it for distortion analysis in the TCN network;
(vi) articulate adequate power quality specifications for our environment to ensure the protection of public interest.
(vii) suggest measures to be adopted by steel plant owners to ensure compliance with the set performance specification;
(viii) suggest strategies to be adopted by TCN to enforce compliance with set down quality standards by all steel plant owners;
(ix) make any other recommendation that will enhance the maintenance of good power quality at the transmission voltage level.

SAMPLE MEASUREMENTS ON THE NIGERIAN POWER NETWORK

Total Harmonic Distortion (THD)

1. The THD voltage is beyond the normal range (limit 5.0%); the maximum value is 23.6% (phase 3)
2. The THD current is within the normal range (limit 12.0%); the maximum recorded value is 6.3% (phase 3). See figure 29 below for clarification.

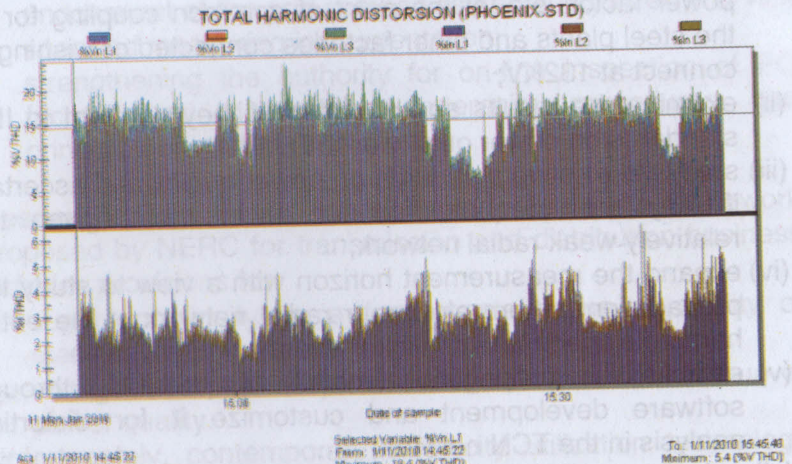


Fig. 29 Total Harmonic Distortion (THD)

D. INDIVIDUAL HARMONIC VALUES

1. The recorded data shows that some of the voltage harmonic values (e.g., harmonic 35, 11, 13, 23, 25, 37) exceeded the acceptable limits. See figure 30
2. Virtually all of the current harmonic values are within the acceptable limits.

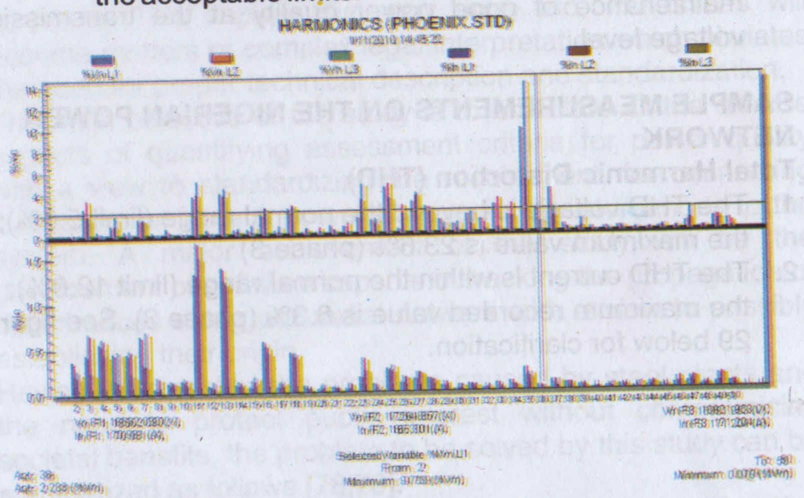


Figure 30 Individual Harmonic Values

Figure 30 Individual Harmonic Values

6. The Hivotec Project

The High Voltage Technology Centre (HIVOTEC), a joint project involving the University of Lagos (UNILAG), National Electric Power Authority (NEPA) and Asea Brown Boveri Nigeria (ABBNG) was formally conceived in July 2001 with the following objectives [80]:

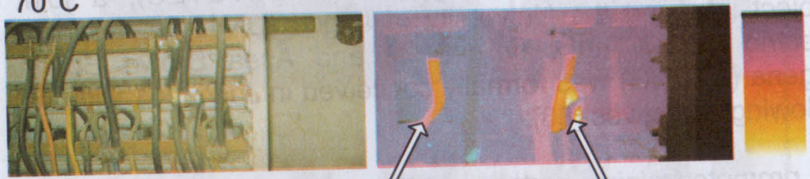
To promote training and research in High Voltage Engineering through undergraduate and post graduate programmes.
Provide the much needed manpower and expertise for NEPA and industry.
Provide modern facilities for industrial High Voltage testing and measurements with a view to acting as certification centre of international standard for HV equipment and devices.
Develop/acquire state of the art techniques for online assessment of HV equipment including condition based evaluation.

I was appointed the Scientific Cordinator of the project in August 2002. This is an on-going project whose major aim is to facilitate the transfer of technology, on the condition based on evaluation of power equipment. This includes diagnostic tools such as infra-red measurements, partial discharge measurements etc, which can be used to determine the service condition of transformers, circuit breakers, insulators, etc.

The second major focus is High Voltage & High Current Testing

LV Busbar System in SENATE House

70°C



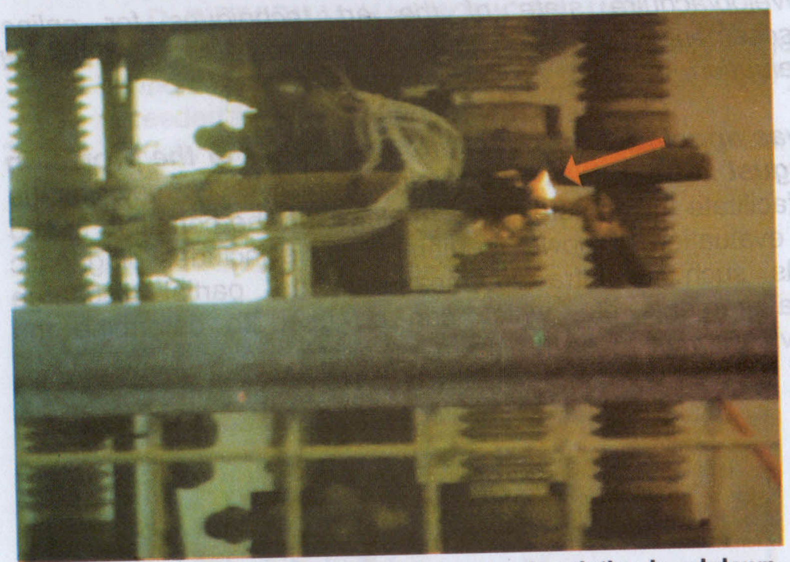
Photo

30°C

Infrared Picture

Fig. 31: Use of thermovision camera on a Busbar

Comment: there are several hotspots around which need immediate repair! The equipment has to have a limited load current.



Experimental setup of 33kV cable showing insulation breakdown (red arrow shows burning end)

THE NIGERIAN POWER SYSTEM

The Nigerian power system, like its counterparts in the developing world, is characterized by deficient available

The Nigerian power system, like its counterparts in the developing world, is characterized by deficient available capacity resulting in low spinning reserve and weak security. Due to low inertia arising from relatively small capacity, frequency swings against load changes are, in most cases beyond the mathematical first order which is assumed in the design of most control equipment. In consequence, frequency errors are high while system collapses (partial/total) are frequent which adversely affect power quality and reliability. Technical losses are also high due to a number of factors including long transmission distances while the level of system automation is far below average. Activities such as LFC is still manually implemented, relying on telephone communication between the operator at the National Control Center (NCC) Oshogbo and his counterpart at a remote generating station. During this period, a key decision on the rate of change of load with frequency has to be taken based on which percentage load adjustments will be made to minimize frequency error.

Against the above background, deregulation has been proposed as a way of improving the electricity supply industry (ESI) in Nigeria. However, deregulating such a power system requires greater considerations than are proposed for other networks in developed economies [1,2]. For instance, in a deregulated system, every Disco can contract power from every Genco and it is the duty of the Transco to implement such contracts using LFC equipment which is currently manual. There are other questions like, who picks the bill of LFC?; how should stabilizing power be valued and compensation effected?; Who specifies the generators on spinning reserve?; Who determines the droop settings?; Is the tariff going to be uniform everywhere in the country given the different costs of transporting power to different locations?; etc. There appear to be more questions than answers but that should not dampen the determination to succeed.

GENERATING AND TRANSMISSION CAPACITY

The country's available installed electricity generating capacity is a little over 4000MW. With the country's population at about

150million, this works out to 27 watts per person. This is not enough for the individual to light a lamp, how much more do any of things listed above that a modern urban centre should do, whether singly or collectively with others.

If we consider that only the Nigerian urban population alone (estimated at 50million, including Niger Republic which is also connected to Nigeria's grid) have access to all of the 4000MW capacity, it will be about to 80 watts per person. It is better, but not much. Table 1 which shows comparative figures for electricity capacity of some countries, says the whole truth about where Nigerian is in the comity of nations.
In other for Nigeria to join the league of world leading countries, we need to raise our electricity generating and distributing capacity to at least (500 watts) x (50 million) = 25,000MW.

TABLE 1: GENERATING AND CONSUMPTION CAPACITIES

COUNTRY	POPULATION SERVED	POWER GENERATING/ HANDLING CAPACITY	PER CAPITA POWER CAPACITY (WATTS PER PERSON)	PER CAPITA CONSUMPTION (KWH PER PERSON PER YEAR)	COUNTRY'S GDP
USA	293.6 million	848,300 MW (year 2002)	**2,889.30**	12,465.94	11,750,000,000,000
GERMANY	82.6 million	115,000 MW (year 2002)	**1,392.25**	6,209.40	2,362,000,000,000
UNITED KINGDOM (England and Wales)	59.7 million	76,300 MW (year 2001)	**1,265.90**	5,742.50	1,782,000,000,000
SOUTH AFRICA	42.7 million	44,650 MW (year 2001)	**1,046.70**	4,243.60	491,400,000,000
BRAZIL	179.1 million	86,020 MW	**480.30**		1,492,000,000,000
CHINA	1,300.1 million	338,300 MW (year 2002)	**260.00**	1,120.30	7,262,000,000,000
INDIA	1,086 million	115,520 MW	**106.31**	582.00	3,319,000,000,000
GHANA	20.7 million	1,762MW	**85.12**	334.26	48,270,000,000
NIGERIA	137.3 million	4,000 MW (year 2001)	**29.133**		125,700,000,000

The System was planned to fail

Until recently, the Nigerian Power System was solely owned by the government. Yet most major projects in Nigeria were designed to have their own power supply separated from the national grid. Typical examples are the Eleme Petrochemicals which has 120MW private capacity, Ajaokuta steel plant, now supplies power to the grid from its "Standby Power Plant", Aluminium Smelting plant in Akwa Ibom state has about 500MW generating plant, NAFCON Port Harcourt had over 100 MW standby plant etc.

These projects are within the jurisdiction of the existing power supply. We only needed to have grown the capacity of our power system to accommodate these new projects. One can therefore say that the failure of our power system is assumed in the design of these projects. A policy shift is urgently required.

Power Sector Reform Agenda

We are all aware of the reform process and its progress, the policy changes and the shifting dates. I am worried about the acute paucity of liquidity in the emerging power market. Presently, the distribution companies delivers about 50% of the cost of power delivered to them. They need to do up to 90% for the system to break even. Now if both the distribution and generating companies are privatized simultaneously, and the Discos fail to collect enough money to sustain the generators, the Gencos will go bankrupt and the entire system will collapse. I would suggest that Discos be privatized first and their revenue collection capacity sharpened before privatizing the Gencos. We should learn from the experiences of other economies who are even more stable than ours. If we insist on privatizing the two simultaneously, then we shall be ready to remove fuel subsidy and enthrone power subsidy at a larger dimension.

Mambilla Hydro Electric Project

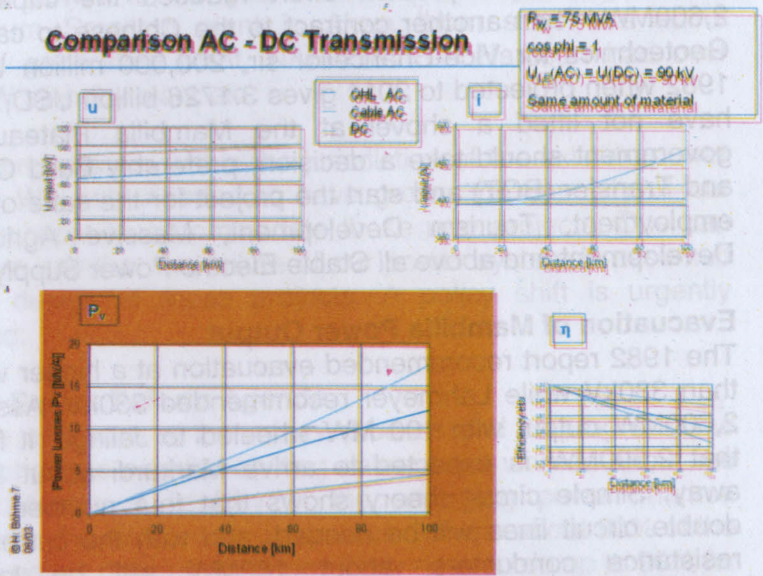
About 1980, the Federal Government of Nigeria awarded a contract to DIYAM Consultants to conduct a feasibility study of the mambilla hydro electric project for the sum of 200 million dollars. In 1982, the consortium submitted a 7 volume report recommending a hydro electric development that would yield 3,900MW. Twenty four years later, in 2006, the same Federal Government of Nigeria awarded another contract to Lahmeyer Consulting of Germany for 300,000 million naira to review the

1982 report. This present effort reduced the capacity to 2,600MW. Then another contract to the Chinese to carry out Geotechnics Mr Vice-Chancellor sir, 200,000 million USD in 1982 when projected to 2011 gives 3.1726 billion USD, yet we have not lifted a shovel at the Mambilla Plateau. The government should take a decision, preferably Build Operate and Transfer (BOT) and start the project for the sake of youth employment, Tourism Development, Massive Agricultural Development and above all Stable Electric Power Supply.

Evacuation of Mambilla Power Output

The 1982 report recommended evacuation at a higher voltage than 330kV while Lahmeyer recommended 330kV. Assuming 2,600MW output with 100 MW wheeled to Jalingo, it follows that 2,500MW is expected to arrive Markurdi about 300km away. Simple circuit theory shows that four number 330kV double circuit lines will be needed, and with the current low resistance conductors, about 180MW will be lost to transmission to Markurdi. At a tariff of 5 naira per kwh, the loss amounts to 21.6 million naira a day or 7.884 billion naira per annum.

Makurdi requires just 100MW or less than that, the bulk of the power is going down south which makes the losses unimaginable. My informed opinion is that the bulk of the power (say, 1500MW) be transmitted by High Voltage DC (HVDC) transmission beyond Makurdi while the rest is wheeled by 330kV line that can feed villages along the route. The advantages of HVDC over HVAC is shown on the attached diagram below.



REPOSITIONING UNIVERSITY OF LAGOS FOR THE EMERGING POWER SECTOR REFORM

Mr Vice Chancellor sir, this great university has tremendous comparative advantages over others in Nigeria, in the following ways

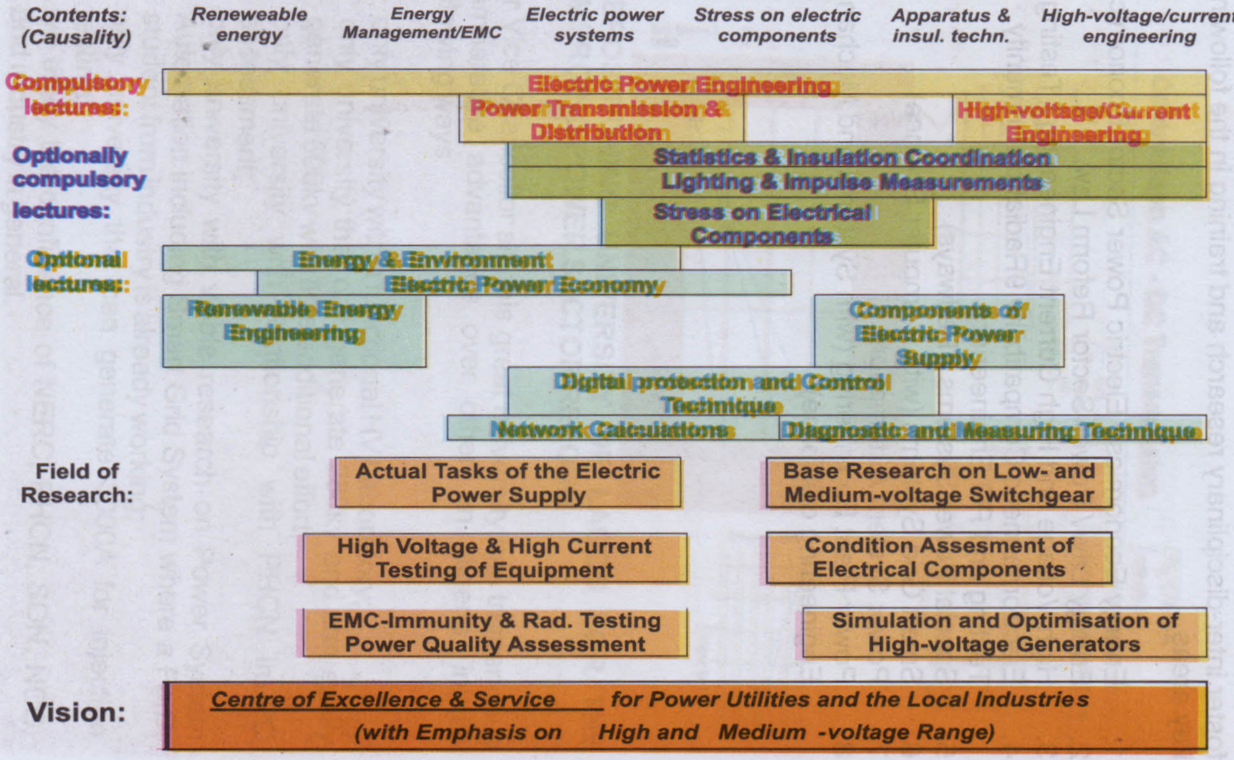
- only university with a functional HV Laboratory;
- only university that can generate 280kv and can easily generate 600kv with little additional effort;
- only university with relationship with PHCN in PQ assessment;
- only university with viable research on Power System Automation including Smart Grid System where a Ph.D. student from industry is already working;
- only university that can generate 3000A for injection testing;
- we enjoy the confidence of NERC, PHCN, SON, NCC, and Industry in general.

With the above rare advantages, it is recommended that Unilag set up a modern Electrical Engineering Program to

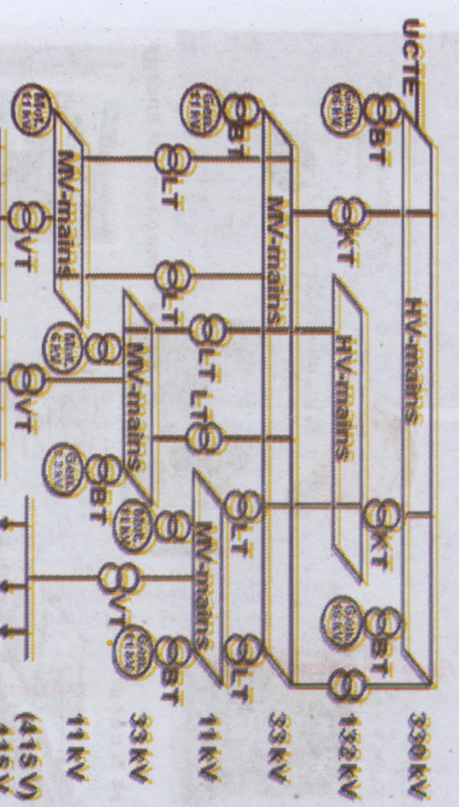
foster inter-disciplinary research and training in the following key areas

1. Energy Economics / Electric Power Sector Economics.
2. Energy Law / Power Sector Reform Law.
3. High Voltage and High Current Engineering / Testing.
4. Electromagnetic Compatibility 9Radiation/Immunity Testing and PQ Engineering).
5. Special Power Systems (Railways)
6. Smart Grid Systems (with Computer Science).
7. Power System Automation
8. Power Plant Engineering (with Systems and Mechanical Engineering discipline)

MODERN ELECTRICAL ENGINEERING DEPARTMENT



POWER TRANSMISSION & DISTRIBUTION



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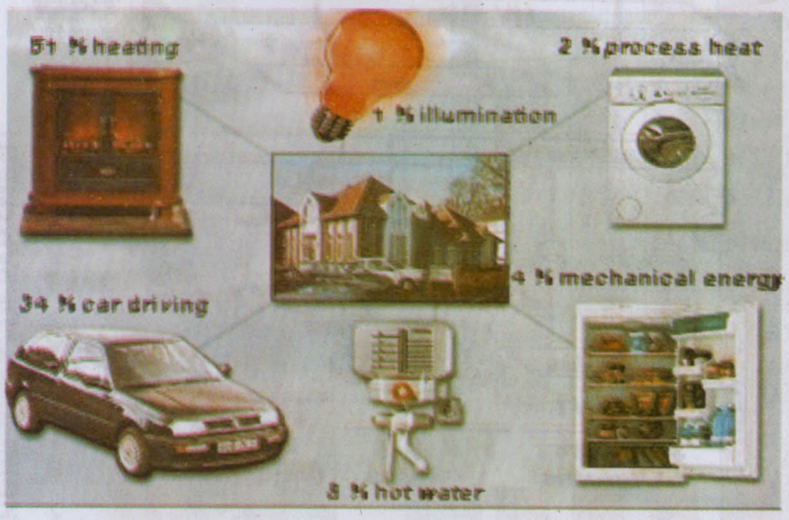
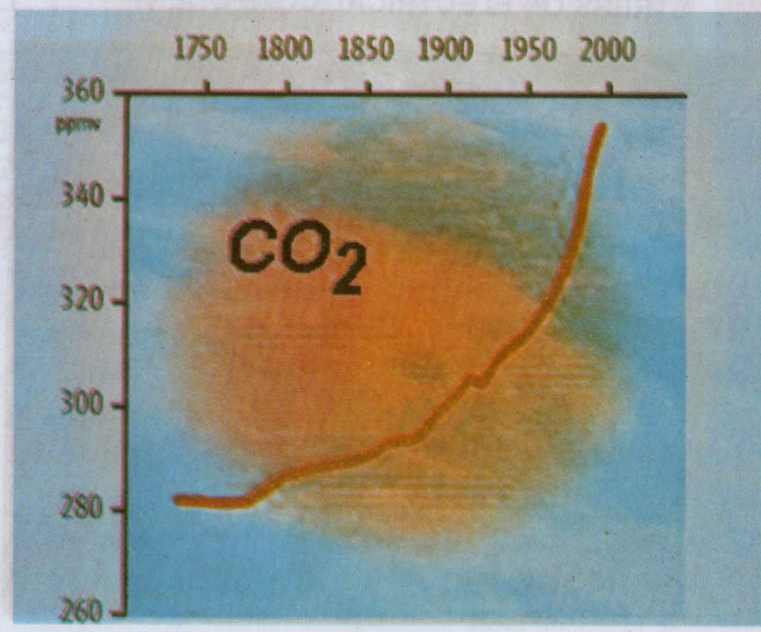
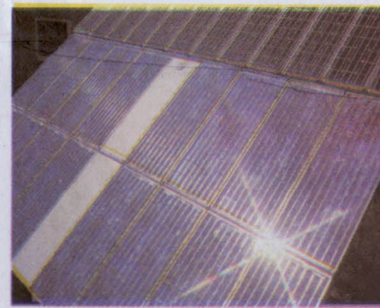
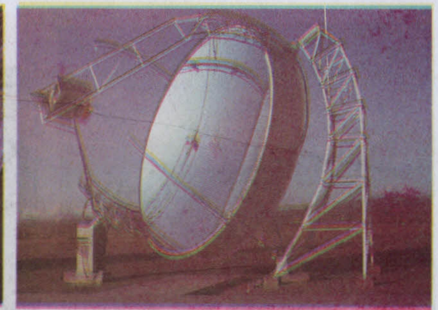
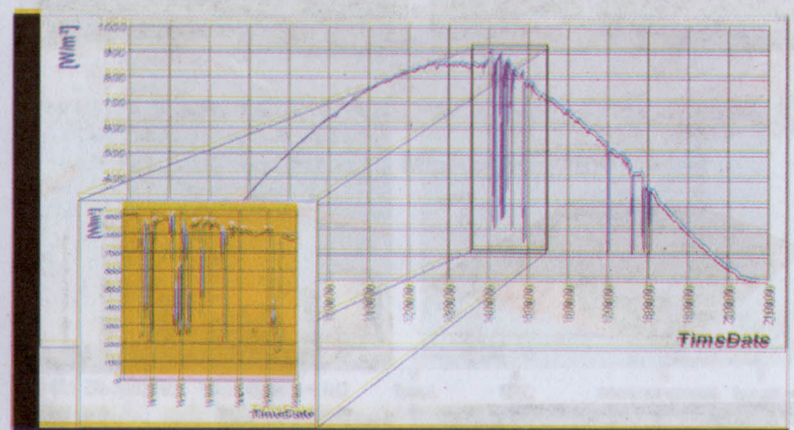


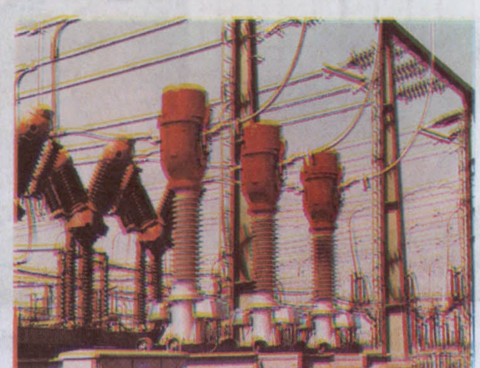


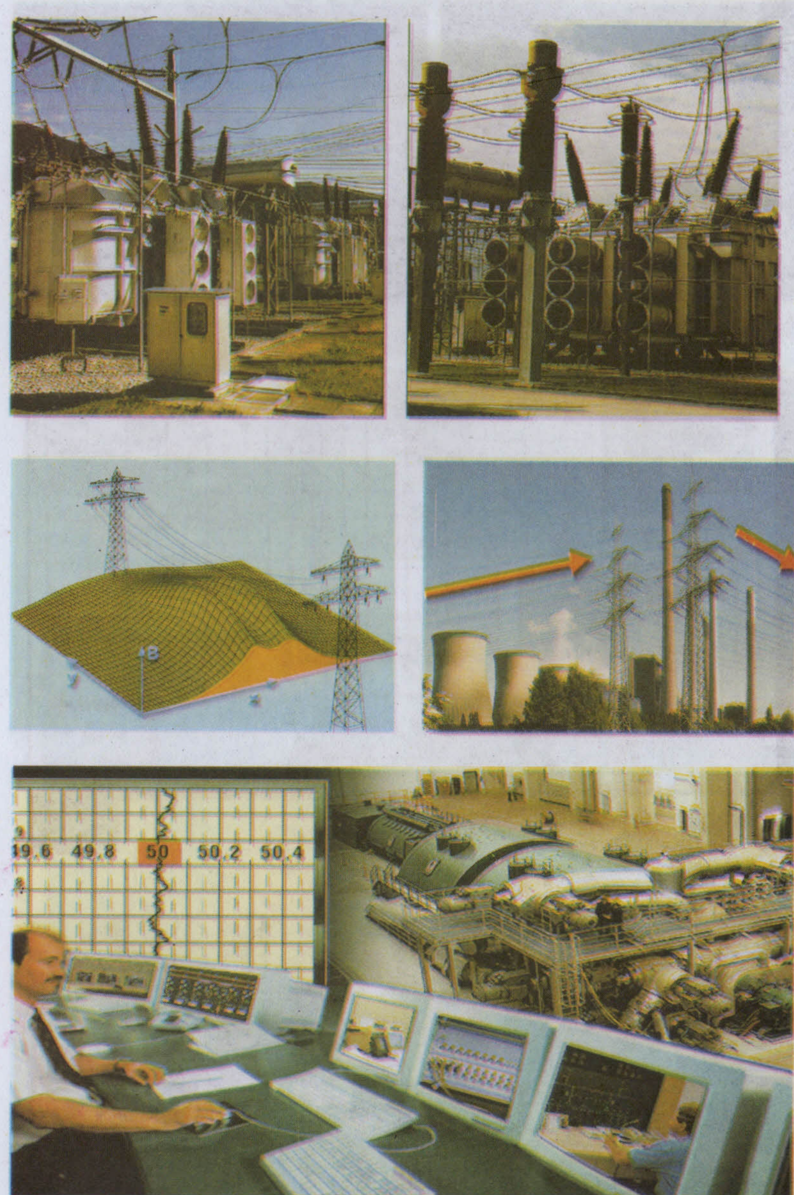






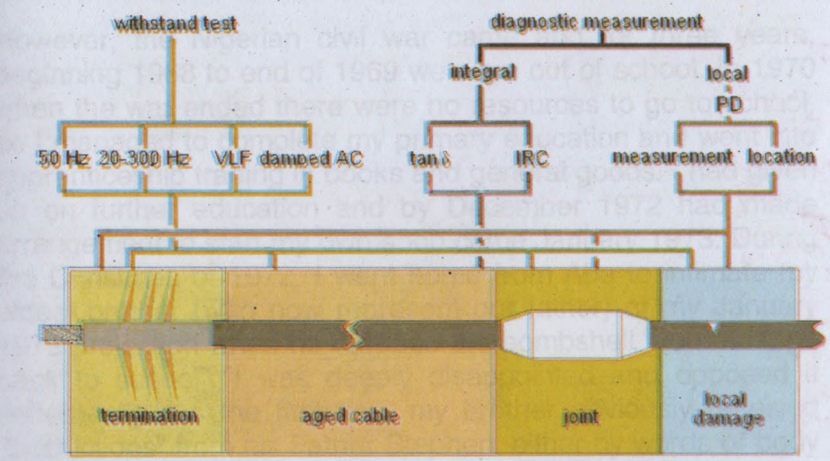
Chemnitz 10.5.2001





Condition Assessment of Electrical Components

DIAGNOSTIC MEASUREMENT



CONCLUSION

Mr Vice-Chancellor sir, distinguished guests, the electric power supply industry in Nigeria is fast changing for the better and as one of the premier universities, Unilag needs to key into this wind of change. In line with the practice in advanced economies where universities act proactively to position themselves in readiness for emerging government policies, especially where they have comparative advantage. I urge your administration to act accordingly. A modern Electrical Engineering Department will be the pride of this university and I can foresee emerging research groups winning the LNG price for science and technology consecutively for several years. What is required of the university is more of a will power than cash power, and among the research groups, cooperation instead of unhealthy competition. After all, the sky is enough home for all the birds, so we shall build our home as big as the sky to accommodate all and sundry.

ACKNOWLEDGEMENTS

I have come this far because the grace of God is with me and He has showered His blessings upon the works of my hand. Nothing could be more fulfilling than this day when all of us are gathered, in good health of mind and body, to witness the delivery of my inaugural lecture. May honour and glory be His forever Amen.
That I went back to school in 1973 to start a five year program leading to West African School Certificate Examination (WASCE) was largely due to the wish of my late father "Onyenkuzi" (Teacher) Stephen Okafor (1904 -1967). I had finished primary five in December 1967 at the age of ten and had projected that I would take the WASCE in 1973, graduate in Medicine at age 22 and marry at age 25. How these projections were formulated in my brain at that tender age is something I cannot fathom up to this day. I still remember them, anyway.

However, the Nigerian civil war came and for three years, beginning 1968 to end of 1969 we were out of school. In 1970 when the war ended there were no resources to go to school, so I managed to complete my primary education and went into apprenticeship trading in books and general goods. I had given up on further education and by December 1972 had made arrangement to start my own shop come January 1973. During the Christmas of 1972, I went home from Aba to intimate my eldest brother (who now represent our father) of my January 1973 projection when he dropped the bombshell "you must go back to school". I was deeply disappointed and opposed it vehemently. As the first son, my brother obviously received "instructions" from his Father Stephen, either by words or body movement, that all of us must go to school. Therefore, his words were spoken with irrevocable finality. For a few days, my position was maintained, but nobody needed to tell me I was fighting a lost battle because even some of my siblings who supported me initially got converted. Eventually the following dramatic conversation ensued between me and my brother.

Frank: What is the highest degree obtainable from a university?
Brother: Ph.D.
Frank: Then I must earn a Ph.D.

Mr Vice-Chancellor sir, this is the real beginning of my journey to this podium. May the soul of "Onyenkuzi" Stephen Okafor rest in perfect peace (Amen).

I therefore, acknowledge my eldest brother Chief Barth Ozoekwe Okafor and his spouse Ifeoma for their love and friendship. For our mother Mrs. Cecilia Okafor, whose lot it was to rear six children after the death of her spouse, I say a big thank you for a job well done. Though she is about ninety years of age, her brain still remains the custodian of events that happened even seventy years ago. I also thank my other siblings. Theresa, Christopher, and his spouse Calister, Christy and her spouse Barrister Ifeanyi Udeogu and extended brothers Chief Mike Uchegbu and her spouse Ngozi as well as Prof. Anhachi Uchegbu for their sacrifice especially during the difficult old days. May the souls of my sister Josephine and her spouse Chief O. Obiorah as well as those of my uncles and aunties Mr Joseph Nwosa, Mrs, Anikpe, Messrs, James Anyionwu, Nicholas Anyionwu, Simon Udo and my Pal, Uchenna Nwabufor continue to rest in the bosom of the Lord (Amen). And for my Late Sister Josephine, who was supposed to represent my mother at this inaugural lecture, she came, she fought, she conquered, and she exited when the ovation was loudest.

So in 1973, I registered in a village school "Boys Secondary School Ogidi" as one of the 1st set of students. The school had just been re-opened after a closure occasioned by military "rationalization". Then, I met great teachers like Late Mr John Izuora (the Principal), Mr. Emma Okonkwo, Mr Uzoukwn , Mr Ekpunobi and late Miss Egbuonye amongst others. Early interactions with them helped a great deal in moulding my character especially my tenacity to excellence and perseverance. The motto of the school is "Perseverance Conquers".

I also met great classmates like Engr. Chike Enetanya, Gordian Ifebinike and late Edwin Igwebuike. These men were of no mean intelligence and we regularly converged to exchange notes on recent successes on the solutions of exercises in our mathematical "bible", General Mathematics by Channon et al. My association with them gave me the first training on healthy competition.

Our role model was Prof. Chike-Obi, the legendary mathematician whose presence in the University of Lagos may have influenced my decision to come to "this great school". I acknowledge with humility a distant uncle and a fellow village man from Ikenga-(Obododike) (Ikenga, the home of the brave) Prof. Chinua Achebe who lit the candle with which we saw the narrow path to academia, I hope I have not totally disappointed you.

To my old Boys Association especially the Lagos Branch, I thank you for your support and encouragement. Special mention can be made, in no particular order, of people like Barrister Azubuike Okaroh, Mr Chris Ndulue. (MD Arik air), Mr Okey Okafor (Chairman of Chioce Insurance brokers), Captain John Okakpu etc. The entire Ogidi community in Lagos led by the President, Sir Peter Egbuna, fully represented here I am humbled by the turn out, after all, it is the number of followers that makes the prestige of a king (Gidi Gidi bu ugwn eze). In the same vein, I acknowledge my fellow Ogidi men and personal friends Bar. Sam Egbuchunani and Engr. R.O.Okeke, C.E.O. of National Power Training Institute of Nigeria(NAPTIN) and their spouses Chinwe and Ogo for being there for me all the time.

In 1979, I enrolled in year 1 to start a 5 year program in the Department of Electrical Engineering University of Lagos. I was privileged to meet two great teachers, Dr O. Ajayi (heavy current) and late Dr. T.A. Kasim (Light current). Both greatly influenced my interest in academics.

Suffice it to say that the vacuum created by Dr Kasim's exit remains open till this day because it will take three dedicated men to fill the gap. May the soul of Dr Kasim rest in perfect peace (Amen). As for Dr. O. Ajayi, the Grand Father of Electrical Engineering Department, I will just key into the proposal made by late Prof. O.O. Ijaola while delivering his inaugural lecture in this same auditorium in 1998 and I quote "I believe that the University of Lagos through the Welfare Board should introduce .....mentorious service awards. If this is done, people like Dr. O Ajayi ..... will have his name deservedly recorded in the history of this university and in particular in that of Department of Electrical Engineering as a great scholar worthy of emulation". Later I met Prof. Awosope and Dr. Awobamise, a brilliant Control Engineer who supervised my undergraduate project. Our friendship still sustains till today notwithstanding that he left Unilag officially in 1987. The greatest fortune I had in Unilag was my meeting with Prof. James Katende in 1987 shortly after he came back from Italy. This gentleman was to become instrumental to the realization of my Ph.D. dream. He introduced me into sliding mode control theory and together with Professor Awosope supervised my Ph.D. research. I really owe him a lot. I must also acknowledge his amiable wife Opi who would always cook our food while we brain stormed on my research papers. 'Opi Chick', I thank you so much with your children Jesse, Amalu, Francis and John. I deeply appreciate my colleagues in the electrical engineering family: Prof Wole Adengbenro (Director NCEEC), Prof. Ike Mowete (HOD), Drs Ayorinde, Oluseye, Gbenga-ilori, Osunde, and Engrs. Adelabu, Abdulsallam, Odekunle, Akinade, Olobaniyi, Tunji, Alayonde for sustaining a conducive environment to work. I also appreciate the secretarial members of staff in the Department at that time, notably Mr. Mark Anya who typed my Ph.D., thesis and late M.A. Ojo. The current secretarial are hereby acknowledged for their efforts to move the Department forward. To my senior colleague Prof. R.I. Salau, and others: Dr Akinbulire, Dr Adetona and Adeola Balogun, Engrs Felix Kalunta and Omeje Osita. I thank you for collaborating with me in my research endeavors.

In the wider faculty, the discipline and hard work of Prof. Alfred Akpoveta Susu (NNOM) attracted me to him in the nineties and I have enjoyed his friendship ever since, apart from developing tenacity for hard work. The Program of US Africa

Research and Education collaboration sponsored by the National Science Foundation (NSF) of USA and anchored by Prof. James Momah of Howard University in Washington DC, brought Distinguished Prof. V.O.S Olunloyo (NNOM) and me together. This gentleman possesses extraordinary skill in combining town and gown activities seamlessly and I learnt a lot from him.

Mr Vice-Chancellor sir, may I with a deep sense of responsibility thank this great university for providing an enabling environment for me to work and enjoy. I thank the Vice-Chancellor, Prof. Adetokunbo Babatunde Sofoluwe for engineering this enabling environment. Your worthy assistants, the DVC (A&R) Prof. Modupe Ogunlesi and DVC-MS Prof. R.A. Bello are doing wonderful works and I appreciate them for that. The Registrar, Olurotimi Shodimu Esq (olu-70) has been a friend since the school days and I thankfully acknowledge his support. I also acknowledge my friend the Bursar Mr. Odekunle. It is very difficult for me not to acknowledge the former Acting Bursar Mrs. Serano and the Librarian Dr Okanlawon Adediji personally. In 2001 I was to keep a medical appointment in Germany, and approval for the university contribution of ₦200,000 came by 4.00pm on the day of the journey. Mrs. Serano, as the Deputy Bursar paid the money in 30 minutes. Also Late July 2010, my Department went to Badagry for an academic retreat in a free bus offered by the Librarian. May God reward both of you abundantly.
Prof. Tolu Odugbemi, the immediate past Vice-Chancellor exhibited rare courage in the course of processing my professorial appointment. The interview and council approval lasted just two weeks and I would want to appreciate him for that selfless service.

In pursuit of excellence under the HIVOTEC project, I visited a number of universities and industries in Germany, as a member of a delegation led by Prof. Oye Ibidapo-Obe, the then Vice-Chancellor in 2002. I thank Prof. Ibidapo- Obe for making me a member of that delegation and would also want to appreciate the members of the Hivotec team, notably Engr. Joe Makoju (former C.E.O of PHCN), Engr. Wolfgang Pfiffer (former C.E.O. of ABB Nigeria), late Prof. Olu Ogboja of blessed memory (then Dean, Faculty of Engineering), Engr. Manfred Woehe (consultant to ABB Nigeria who prepared the feasibility studies for Hivotec) and Mr. Bonny Odiri who later became the Director General. The efforts of Hivotec administrative staff, Mrs. Uche Okonkwo and Mrs. Irene Oguns are hereby acknowledged.

I recall with nostalgia how I accompanied the indefatigable Prof. J.A. Omotola of blessed memory to the palace of paramount ruler of Ijagun, over a land matter. We were received by the Oba-in-council and that taught me to keep a link with all levels of workers within my profession.

Engr. F.A. Somolu is no doubt the best Power Systems Protection Engineer Nigeria has produced, and I thank him for imparting that rare knowledge into our M.Sc students in theory and practice. He invited me in 2007 to join him in the Presidential Advisory Team on Power Sector Reform and I learnt a lot about government business. Just as Engr. Ernest Ndukwe (Chairman Open Media) and Dr. John Mbonu (Director PWC) are always willing to assist the Department whenever we call on them. May providence smile at you always. I will also appreciate the following for their support and friendship: Dr Sam Amadi (C.E.O Nigerian Electricity Regulatory Commission NERC), Engr. S. Labo (C.E.O. PHCN) Engr. A.S.A. Bada (C.E.O. TCN) Engr. Sola Akinrinaye (ED-TSP-TCN) Engr. Marice Iyorha (ED-SO, TCN), Engr. Mike Uzoigwe (C.E.O. Egbin Power Plc), Engr. Amoda (C.E.O. Eko Distribution Company), Engr. John Ayodele (Director Power Ministry) and Mr James Olotu (C.E.O. Niger Delta Power Holding Company). Others are Engr. K. Achife (General Manager Gas and IPP, PHCN), Mrs. Efunu Igbo (General Manager Corporate Affairs, PHCN), Engr. F. Zachaaeus (General Manager PSPD-TCN) and all my friends in the In-house Grid Study Team. I appreciate you all.

From July 2000 to June 2001, I was a guest of the German Research Foundation (DFG) and was hosted by Prof. W.

Hofmann. Chair of Electrical Machines and Drives at the Technical University of Chemnitz. I thank Prof. Hofmann and DFG for the gesture, and I appreciate my other colleagues Messrs Said El-Barbari and Baldiuno Rabello.

Two years later, in January 2003, I was back at Technical University of Dresden, Germany as a visiting Professor in the Institute of Electrical Power and High Voltage Engineering for the Hivotec project. I will remain eternally grateful to the head of the institute, Prof. Shegner, the Head of the High Voltage Group, Prof. Grossman, Drs Loebl and Engelman for their tremendous support and encouragement. To Prof. Ralph Rogler of the University of Applied Sciences Dresden, as well as Drs Hauschild and Ralph Bergman of High Volt Pruftechnik Dresden, I say a big thank you for the co-operation I received. In the normal course of business, I met Mr. Tunde Esho, Mr Akinbami, Mr Sola Oladokun and Mr. Deji Benedict in the nineteen nineties. My association with these great men changed my living conditions up to this day and I will ever be grateful to them.

May I acknowledge with thanks the contributions of Mrs. Uche Okonkwo, Miss Uduak Ntia and my secretary, Roluga Temidire towards the preparation of this lecture. And to my in-laws, the Chukwu Family represented by Nze F. P. And Mrs Ezinne Chukwu. I thank you for the Jewel you gave me as a wife. Special thanks to my parents in-law, Mr. Luke and Madam Rose Chukwu, for their patience with me. The younger Chukwus notably Prof. Obinna & Mrs Ngozi Chukwu, Pastor Laz & Attorney Tracy Udenwagu, Mr. Damian and Dr. Obioma Aguocha, Mr. Kelechi and Onyedi Chukwu, Mr. Martins & Mrs Chika Ekwems, Mr. Udeogalanya & Mrs Yewande Chukwu and Mr. Ahanna & Engr. Rose Ejidike, have been very supportive and I thank them all.

To my household and all the members that make it interesting: Onyeka, Kenechukwu, Adione, Chibeze and Aunty Anayo, I salute your courage. Finally, I appreciate my wife Mrs. Ogechi Uzonwadioti Okafor for keeping the home front conducive for human development. It would have been extremely difficult to get to where I am today if not for her understanding.

To my children Chibuzo, Obianuju, Ogochukwu, Chinedu and Chukwudi, I thank you for tolerating my usual absence and pray that your struggle to excel will yield substantial benefits.

Mr. Vice-Chancellor sir, members of the press, distinguished ladies and gentlemen. I thank you for listening.

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