Half a Century of Computer Methods in Power System Analysis, Planning and Operations Part II: Glenn W. Stagg and His Contributions to Advancing the Technology

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Abstract -- This paper is the second paper devoted to the contributions of Glenn W. Stagg to the advancement of the stateof-the-art in power system analysis, planning and operations. It provides a critical review and assessment of his work in the fields of: computer method development; faults and short circuit analysis; load-flow and stability computation techniques; and energy management systems. Also emphasized are the far reaching consequences of Glenn W. Stagg's seminal work, which eventually opened the road for some of the advanced applications of today that were not even conceivable during those pioneering years. It is hoped that this succinct overview of his work will serve as motivation and inspirational example for students, researchers and power system professionals.

Index Terms – Computer methods in power system analysis; generation control; network analysis; SCADA/EMS.

I. INTRODUCTION

THIS is the second of two papers honoring the memory of Glenn W. Stagg in the special panel session *Half a Century of Computer Methods in Power Systems. A Tribute to the Memory of Glenn Stagg and Jorge Dopazo.*

Glenn W. Stagg's contributions to the introduction and development of techniques in virtually all the areas of modeling, planning and operating utility systems cannot be overemphasized, but they are most prominent in:

- Digital computer analysis of power systems
- Generation control and scheduling
- Real-time network monitoring and analysis
- SCADA/EMS architectures and implementation strategies for large systems
- Continuing openness to, and support for, new and nascent technologies.

In order to avoid repeating what was said in the Part I of this paper, we will go directly to the point and review the key achievements of Glenn W. Stagg in the fields of: computer method development; faults and short circuit analysis; loadflow and stability computation techniques; and energy management systems.

In order to better grasp the relevance of these topics, however, it may be helpful to begin by identifying his key conceptual and technological breakthroughs contributed by this industry pioneer.

II. KEY CONCEPTUAL AND TECHNOLOGICAL BREAKTHROUGHS

Glenn W. Stagg's work at American Electric Power Service Corporation (AEP) during the infancy of digital computing has left long lasting marks on the field of computer methods in power system analysis, planning and operations.

For example, running real-time load-flows and stability calculations in a SCADA/EMS environment, to mention just two of the many tools that are now used on a daily basis in power system control centers, is taken for granted – but back then, in the late 1950s and early 1960s, the digital computer was a novelty and the landscape of digital techniques for network analysis was nearly empty.

It is precisely from this perspective of novelty that the major *conceptual breakthroughs* contributed by Glenn W. Stagg must be considered, e.g.:

- Introduction of iterative methods for computing loadflows
- Using large digital computers to perform power system simulations
- Expanding the scope of SCADA systems with advanced applications, thus eventually leading to the SCADA/EMS
- Generation control and optimization.

In this context, Glenn Stagg's *technological breakthroughs*, which may or may not have been obvious at that time, today shine with crystal clarity.

For example, his vision to use large general purpose computers in SCADA/EMS at a time when the dedicated process control computer was king was vindicated several decades later when the special process control computer all but disappeared, and virtually every single control center on earth uses general purpose workstations and PCs to monitor and control the power system operations.

Other areas of technological breakthroughs include performing interactive computations as opposed to batch processing, e.g., the Interactive Load Flow System introduced in the early 1970s, and envisioning the SCADA/EMS environment as a corporate data repository.

Paper PSE-11 PSCE0208 to be presented at the Panel Session "Half a Century of Computer Methods in Power System Analysis, Planning and Operations. A tribute to the Memory of Glenn W. Stagg and Jorge Dopazo", IEEE Power Systems Conference & Exposition 2011 (IEEE PSCE'11), Phoenix, AZ, March 10-15, 2011

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Using a classification criterion familiar to power system engineers, the key conceptual and technological breakthroughs contributed by Glenn Stagg will be grouped respectively into Digital Computer Applications and SCADA/EMS and briefly reviewed in the following.

III. DIGITAL COMPUTER APPLICATIONS

Glenn Stagg was undoubtedly at the forefront of the application of digital computers to power system analysis and operation.

He collaborated with several other brilliant colleagues such as Kirchmayer, Glimn, El-Abiad, and Dopazo in publishing the early papers on a variety of power system applications. These papers describe in clear and comprehensive detail how techniques and algorithms can be developed for applying digital computers to important and critical electric utility planning, design and operation functions. These papers stand out for the elegance and completeness of the exposition without leaving anything as "as an exercise to the reader." In this paper we include some excerpts from his published work which illustrate his clarity and vision.

In [3, 1976, Bibliography in the previous paper], Glenn states in relation to Application Programs in EMS:

"There are three tests that should be considered in specifying applications. First, the application must technically feasible Second, the proposed application must be economically feasible Finally the proposed application must be operationally feasible... ... it should be possible to develop the control, data entry, and information display capabilities for effective and efficient use of the program"

Astonishingly, this wise advice in 1976 has not been understood by modern day consultants resulting in vast cost and schedule overruns in many EMS projects.

In [15], Glenn addressed the EMS obsolescence issues that have plagued the industry for many decades. He asserts:

"It is essential therefore for a utility hoping to deal with the future to commit itself to equipment that has significant expansion capability. This capability should encompass the installation of additional components as well as replacement of older units... ... that will not require changes to the program systems"

As early as 1955 [22, Bibliography in the Part I of this paper] he clearly describes an "economic dispatch":

"The incremental fuel cost slide rule, now in operation at the Central Production and Coordination office in American Gas and Electric Service Corporation is used in load allocation procedures to compare the fuel costs, adjusted for losses for the various units of the system. It consists of a logarithmic incremental fuel cost scale, a movable strip of each generating unit, a moveable fuel cost adjustment scale, and a penalty factor scale." Although he made contributions in many areas and published numerous papers (see bibliography in the previous paper), we will concentrate in this section on his most seminal contributions to applications which were essential if digital computers were going to be widely adopted for power system simulation. These applications which form the core day-to-day activity of planning engineers are:

- Load Flow
- Transient Stability
- Short Circuit (Fault) Analysis.

He felt that unless the user community, which relied heavily on these studies, fully accepted the digital computer implementation, they would be reluctant to accept the more rarely used applications. To illustrate his basic philosophy and attention to detail we will use only the book he co-authored with Professor Ahmed El-Abiad of Purdue University [11].

This book clearly demonstrated his commitment to making certain that the topics were addressed clearly, completely and with many worked out examples, many of which were formulated and solved by his highly skilled colleague Jorge Dopazo, whom we also remember today.

This book was for many years a standard reference and remains an excellent introduction in this area. It has been used as a text book in most recent graduate programs at Universities around the world and even today remains an important source for material not found elsewhere.

In it, Stagg and El-Abiad deal with the mathematical preliminaries and with the actual power system problem. Thus in the Load Flow section they describe in detail the formation of the Z-bus, Z-loop and Y-bus matrices-(material usually found in books on circuit theory and not easily accessible to power engineers until the publication of the book)and then formulate the load-flow problem. They then describe the Gauss Seidel and Newton Raphson solution techniques. Examples using both solution techniques are given as well as flow charts for developing a load-flow program. We provide below an excerpt for Chapter 8 "Load Flow Studies"

"Gauss Iterative Methods Using Y_{bus}

The solution of the load-flow problem is initiated by assuming voltages for all buses except the slack bus, where the voltage is specified and remains fixed. Then currents are calculated at for all buses except the slack bus "s" to form the bus loading equation:

$$I_p = \frac{P_p - jQ_p}{E^{*}_p} \ p = 1, 2, \dots, n, \ p \neq s$$
 8.3.1

where *n* is the number of buses in the network. The performance of the network can be obtained for the equation:

$$I_{bus} = Y_{bus} E_{bus} \qquad \qquad 8.3.2$$

Selecting the ground as the reference bus, a set of n-1 simultaneous equations can be written in the form

$$E_{p} = \frac{1}{Y_{pp}} (I_{p} - \sum_{\substack{q=1 \\ q \neq p}}^{n} Y_{pq} E_{q})$$

$$8.3.3$$

$$p = 1, 2, \dots, n, p \neq s$$

The bus currents calculated for equation (8.3.1,) the slack bus voltage, and the estimated bus voltages are substituted into equation (8.3.3) to obtain a new set of bus voltages. These new voltages are used in equation (8.3.1) to recalculate the bus currents for a subsequent solution of equation (8.3.3). The process is continued until changes in all bus voltages are negligible"

It should not be hard to write the basic algorithm based on this excellent yet brief description. Of course, production grade programs have to have many more capabilities and features. They then go on to describe the Gauss Seidel variation. Although the Gauss Seidel method is no longer the method of choice in Load Flow programs, it remains as important technique in many special cases, and the Stagg El-Abiad book remains the only source of a comprehensive treatment of this early solution technique. The work done to determine optimum acceleration factors for convergence of this method remains a model exposition for a practical problem in a highly theoretical environment

In Chapter 5 - Three Phase Networks, both the sequence transformation and the Clarke abo components are described. The sequence transformations are then used in Chapter 6-Short Circuit Studies in the treatment of unbalanced faults. In these chapters, the use of Z-bus, Symmetrical Components and commonly accepted simplifying assumptions are explained. Again, examples and a flow-chart are provided. And the exposition is thorough and complete. It is not necessary to refer to other books or papers to fill in the details. There is enough material on symmetrical and Clarke components and numerical integration in a later chapter for the practitioner; only those seeking a more theoretical background would need to refer elsewhere but not for what is needed for their purpose.

In the introduction to Chapter 6, Stagg and El-Abiad note:

"The bus frame of reference in admittance form was employed in the first application of digital computers to short circuit studies. This method..... used an iterative technique and required a complete iterative solution for each fault type and location.Consequently the method was not adopted generally.

The development of techniques for applying a digital computer to form the bus impedance matrix made it feasible to use Thevenin's Theorem for short circuit calculations"

Of course, the formation of Z bus was described comprehensively in the book and used for Short Circuit calculations.

Chapters 9 and 10 on Numerical Solution of Differential

3

Equation and Transient Stability respectively are a model of exposition. There is a clear explanation of the Euler's, modified Euler, Picard, Runge-Kutta and Milne's predictor corrector methods. The synchronous machine model including the swing equation, the d-q axis phasor diagram and the electrical equations (except for damper windings) are presented. It must be noted that this was before all the standard models had been established for exciters, governors, prime movers. The derivation of the H constant is also included. Induction machine models are described. Here again one finds that the chapter is self contained and has all of the necessary information for the practitioner without sacrificing theoretical soundness.

One final note about the book: it is a tribute to his meticulousness that there were virtually no errors in any of the sample problems nor were there many typographical errors. He edited the material himself and took pride in it. He acknowledged in the Preface, the excellent work by Constance Aquila (now Constance Healey-Collis) in typing and general preparation of the manuscript.

Unlike most of his collaborators, Glenn was working for a major electric utility, the American Electric Power (AEP) in the Service Corporation based in New York. He was thus able to translate his theoretical contributions into production grade, practical software that could be used by AEP staff.

One of the authors was responsible for the development of the Transient Stability program which Glenn insisted had to be able to handle large networks (up to 2000 buses); must have detailed synchronous and induction machine models (including the E_d " and E_a " differential equations); must have the ability to synthesize arbitrary excitation system models; and use the fourth order Runge-Kutta method and run efficiently on the IBM 360 computer (this was in the late 1960s).

He insisted, in spite of the protests by us, that the entire program be written in Assembly language in order to meet the performance requirements and stay within memory constraints. In fact, as shown subsequently in the section Interactive Load Flow System, "minimizing processing overheads and computer resources, such as core and secondary memory" was one of the key software design objectives in those pioneering years.

The 2000 bus Load Flow program had been developed and had finally convinced the user community that the digital computers could replace the analog computers even if they did not get a "feel" for the system - the reason for the initial resistance. Of course, in the days of batch processing the execution time was not quite noticeable to the user as it is today but nevertheless minimizing it remained a cornerstone of the development. These Load Flow, Transient Stability and Short Circuit programs were used at AEP for almost two decades.

In spite of the large number of staff in the Computer Application Division at AEP, Glenn remained open to getting software developed elsewhere and was not "a not invented here" individual. When one of the authors informed him

about the breakthrough work of Hermann Dommel at BPA and the possibilities that the EMTP program presented, he immediately acquiesced to getting and installing it in-house. The acceptance of this program presented an even greater challenge since the dependence on the Transient Network Analyzer (TNA) was strong and it was trusted. However, AEP was investigating the use of single pole switching on one of the 765 kV lines and it was decided to simulate this using the EMTP although the study was basically being carried out on TNA. After some initial results demonstrated that the EMTP was giving accurate answers, it was used more and more until some of the key studies were undertaken when the TNA time could not be scheduled. A report based on the EMTP simulations for single pole switching was issued and thought of highly by the transmission planning and electrical engineering departments department.

While we will not cover these, it is noteworthy that he made many contributions in other areas such as economic dispatch, hydro scheduling, state estimation, etc. He also implemented key accounting, payroll and other financial and business applications. By the end of 1960, he had made the AEP computer application department one of the two or three finest in the electric utility world.

He left AEP in 1970 to form his own company (Stagg Systems, Inc.) with three others and continued his emphasis on the use of digital computers when he was one of the first to implement a large Energy Management System on IBM 370 computers. His contributions in the SCADA/EMS field are described in the following section.

IV. ENERGY MANAGEMENT SYSTEMS

A. The early days of online computing in system operations

Until the mid 1950s, telemetering and control in the industry were predicated on analog technology. The first computer manufacturer (Ramo-Wooldridge) entered the industrial computer control market in 1955, followed in 1958 by several other manufacturers; by 1964, closed-loop supervisory control of process plants was already generally accepted by industry [17].

In 1960, the potential economic benefit of digital process control computers was considered sufficiently significant to be applied for automatic dispatching of generation. To a large extent, the system operations computers were applied initially to optimize the allocation of generating output. These were in a hybrid system arrangement, sometimes referred to as digitally directed analog control [5], [6]. In addition to economic dispatch, the computers also performed limited unit commitment calculations, some security monitoring such as off-normal transmission line loading, and periodic logging functions [1].

At AEP, where Glenn Stagg had been appointed as Assistant Vice President of Computer Applications in 1958, the on-line digital computers started to be used for power system operations in the early 1960s. The initial AEP installation aimed at the economic operation of generation and transmission facilities [12], but its focus was soon extended to the real-time monitoring of the current status of the power system [13].

This pioneering work recognized that real-time monitoring and data processing differ from the conventional load-flow problem because of the nature of the information available and the presence of measurement and modeling errors, and led to the industry first successful state estimator implemented at AEP by Dopazo, Stagg et al [3]. The technique was eventually enhanced with the method developed by Schweppe et al [8], [9] and [10] and paved the way to real-time security assessment as we know it today.

B. The insight: using large scale general purpose computers to implement the complete functionality of a SCADA/EMS

Of course, AEP was not the only industry site where power system supervision, control and monitoring technologies were being developed – but Glenn Stagg's unique insight consisted of understanding the many benefits conveyed by placing large scale general purpose computers at the core of the SCADA/EMS architecture. In doing so, he was actually going against the trend prevailing in those times in the industry. An interesting statistic in this regard was published in 1974.

From the 34 "representative modern control systems for power-generation transmission systems" listed in the Table 1 of reference [4], only *two* systems were using large scale IBM general purpose mainframes to handle the full array of control center functions, from supervisory control to AGC and advanced applications such as economic dispatch and state estimation: AEP (IBM 370/165) and Southern Company Services (IBM 370/158).

The architecture of the Southern Company Services SCADA/EMS, which was the first system implemented by Stagg Systems, is shown in Figure 1. Its Supervisory Control and Data Acquisition functionality encompassed: control of data acquisition scans through the communication control units; preprocessing of real-time data for various application programs; preparation of event and substation logs; control of breaker and switch operations; display of substation diagrams and alarms; and control of appropriate CRTs assigned to specific areas for supervisory control.

The System Control Application Programs provided realtime control of generation and formed an integrated system consisting of control and calculation algorithms, operator interactive displays and supporting services. The control functions performed included automatic generation control and economic dispatch.

In addition, the system supported: evaluation of interchange transactions and operating performance; interchange scheduling; generation reserve analysis; energy accounting and data logging; and interactive information display for operator control, data entry, monitoring and alarming. Also performed were additional supporting functions such as: application program scheduling on a time, event or operator request basis; management of core storage and related computer resources used by the application programs; display management for the control and selection of displays; formatting display information and processing of operator requests for data entry and paging; data base management for storage and retrieval of data shared by application programs and resident in core and secondary storage; and off-line generation and reconfiguration of System Control Data Base.



NOTE: READERS, PRINTERS, DISKS & SWITCHES NOT SHOWN

Figure 1 Computer system configuration of the Southern Company Services SCADA/EMS solution delivered by Stagg Systems, Inc. in 1972 (taken directly from [7])

The System Security Application Programs were not available when the reference [7] was written, but they were implemented in 1975 and included: network configuration and state estimation; contingency evaluation; contingency generation scheduling interactive network display for presentation of real-time and study data and initiating, studies; interactive information display for operator control, data entry, monitoring and alarming; and an operator's load-flow.

The functionality of the SCADA/EMS implemented by Stagg Systems at Southern Company Services in the early 1970s seems to be taken directly from a 21st century SCADA/EMS specification. But the most significant aspect of this system was its dual-redundant computer configuration based on large scale commercially available general purpose computers, which allowed Southern Company Services to update the system and keep it "ever green" for approximately two decades without the large costs and operational disruption entailed in what consultants typically call "fork-lift system replacement".

By contrast, the most popular computer choice in the industry at that time was the 16-bit Sigma from Xerox, which had been deployed in 19 of the 34 systems listed in [4]. Everybody knows what happened just a few years later: while the SCADA/EMS consultants were busy specifying the number of processor interrupts, the manufacturers of specialized minicomputers were getting out of business, thus instantly rendering such systems obsolete.

Glenn Stagg's early vision of avoiding the risk of obsolescence by adhering to upward compatible computer architectures coming from manufacturers that are in the market to stay was vindicated twenty years later, when the entire SCADA/EMS industry moved *en masse* to standard workstations and operating systems that are available off-theshelf from major computer manufacturers and can be used either offline or in real-time or both.

The seeds of this concept can be identified in another seminal development that originated at Stagg Systems in the early 1970s: the Interactive Load Flow System.

C. Deploying advanced applications that can be used both offline and in real-time

Towards the early 1970s, the need for load-flow calculations had increased as power systems grew in complexity necessitating the evaluation and analysis of a wide range of proposed expansion plans and operating conditions. In addition, the need to quickly reappraise the requirements for new facilities in light of budget levels had also increased the demand for load-flow calculations.

The utilities realized that it was impractical, if at all possible, to continue to expand engineering staffs to meet such increased study needs and looked for better alternatives to the then prevailing batch processing procedures. This, in turn, led to the introduction of interactive computations, which, for the first time, were acknowledged with a dedicated session at the Power Industry Computer Applications (PICA) Conference in 1975.

During that session, Glenn Stagg presented the Interactive Load Flow (ILF) System [2]. The principal features of the ILF System stem from several critical design objectives. The system was not only to provide the full range of capabilities available at that time for calculating load-flows but also was to be adaptable to a variety of needs and expandable to meet future requirements.

The first major objective documented in reference [2] was to provide a system that: utilized to the fullest extent the capabilities of available video terminals as the user interface while encompassing all of the advanced features and capabilities available with existing load-flow programs designed for batch processing; had the ability to handle large studies of several thousand buses; and was readily adaptable to handle smaller load-flow studies minimizing processing overheads and computer resources, such as core and secondary memory.

The second major objective was to provide a flexible system that could be installed and would operate efficiently both on a *corporate computer facility* utilized for online and batch processing of commercial as well as engineering applications and on a *real-time computer system* for power system control and security assessment.

The third major objective was to provide a system that was readily expandable, not only to meet the needs for calculating larger load-flow studies and to handle additional video terminals, but also to encompass other engineering and control applications.

The first ILF System was installed on an IBM System/370 Model 158 at the Detroit Edison Company, which was part of Detroit Edison's corporate computer facilities and was used also for the Customer Information System (CIS) and the batch processing of accounting and engineering work. The ILF System was then deployed in real-time at Southern Company Services and installed on other SCADA/EMS delivered by Stagg Systems.

Two unique features of the ILF System stand out: the ability to be executed on a widely popular computer available practically in every single power utility on earth; and the capability of being used both offline and in real-time.

By contrast, the "other" interactive load-flow in the industry at that time, known as PSS [16], had been implemented by Power Technologies, Inc. (PTI) on, and bundled with, a Prime minicomputer, and was offered, at least until early 1980s, as an offline-only hardware & software solution.

It took many years for this otherwise excellent product to become a stand-alone program available on standard workstations under Unix and, today, on PCs under Microsoft Windows – thus fulfilling, in some kind of irony of destiny, the vision pioneered by Stagg Systems with its ILF System.

D. Anticipating the future

Glenn Stagg preference for large scale general purpose IBM processors stem from the observation that using off-theshelf computers and software that belong to an upward compatible product line was the key factor in assuring the permanence of the SCADA/EMS solution.

By selecting a mainstream supplier with a track record of providing long-term support and frequently enhanced products with high performance and reliability, he was anticipating the era of *de facto* standards for portability and interoperability.

Towards the mid 1980s, Glenn Stagg arrived at two simple yet powerful concepts: enable the corporate users to access, and benefit from, the huge reservoir of data that originate in system operations; and implement systems that meet a broad range of functional, performance and reliability requirements while avoiding recurring obsolescence.

1) The control center as an information resource

This concept became a major theme in the speeches and presentations conducted by Glenn Stagg in the mid 1980s and was predicated on the philosophy behind the SCADA/EMS solutions delivered by Stagg Systems. In a paper published in 1986 [15], Glenn Stagg notes at the beginning:

"Today, real-time application of computers to power system operations is no longer restricted to simple process control systems, performing only basic data acquisition, control, analysis, and data logging. In the future, these systems will serve as extensive information resources, capable of supporting a broad range of activities necessary to maintain power system reliability and economy. They will provide management, operating, and supporting engineering groups with timely and accurate information regarding the ability of the power system to meet its objectives.

If we recognize the need and plan toward it, the real-time control system will become a major corporate resource of unprecedented magnitude and importance. As this occurs, the role of the energy management system will take on paramount importance. It will become the prime source of operating information, and management, engineering, and operations will depend on this information to provide reliable and economic electric power."

Then, he addresses the power system operations which, at that time, were conducted in a vertically integrated environment and encompassed: planning, which embraced forecasting demand and scheduling the operation of available facilities; operations, which entailed monitoring system performance and controlling facilities to meet demands; and reporting, which encompassed preparing the reports that are essential for modifying future planning and operating strategies to improve operating reliability and economy.

The advent of electricity markets has changed the scope and location of some of these activities, but some ideas are still valid today, such as the need of

"simulation capabilities providing for the computerized evaluation of potential contingencies and the development of emergency operating plans"

and

"the ability to revise automatically forecasts based on current demands, to adjust operating schedules to meet changing conditions in ways that maintain operating reliability, and to re-evaluate the operating performance of the transmission system under normal and emergency conditions".

It is fascinating to read the following assessment in the section *Future Prospects: The Challenge And the Opportunity* a quarter of century after Glenn Stagg wrote it [15]:

"The computer technology necessary to operate an energy management system in a real-time environment is available to the utility industry today. Applying this technology to power systems operations presents a significant challenge, but it is a challenge the industry must rise to meet. Recognition must be given, of course, to the changing business environment in which utilities must operate. The days of seemingly endless supply of low-cost fuels have come to an end. This has changed significantly the traditional methods of planning and operating power systems.

The industry will identify the economies of <u>renewable</u> <u>energy sources</u>, off-system energy purchases and sales, <u>cogeneration</u>, load management, and the construction of <u>decentralized generating facilities</u> [emphasis added] in an effort to seek alternatives to the large, capital-intensive central station plant".

2) Avoiding recurring obsolescence

Glenn Stagg had long been advocating the need to formulate a step-by-step plan to insure that the objectives and benefits of the control system are realized. In a paper that addressed practical aspects of implementing real-time control systems [14], he recognizing the importance of

"identifying the various phases of a control system project with proper emphasis on the development of functional specifications and design specifications. Equally important is the need to establish an effective study and implementation organization".

Incidentally, some of the recommendations documented in reference [14] would be good advice for many SCADA/EMS consultants today, for example:

"It is not intended that the functional specification be a design specification. It should, however, be of sufficient detail to establish system requirements and to provide for the selection of the required computer and related equipment.

Specifying the system requirements in functional terms provides the ability to select program systems and computer facilities that are operational. This reduces significantly development costs and shortens the implementation time. It also eliminates to a large extent the problems inherent in the development of an entirely new system."

Noting the long lead time required to define, design, develop and test the future applications of an energy management system, Glenn Stagg inferred [15] that establishing a long-term development plan was essential and

"as new systems technology advancements develop, utility computer systems must have the built-in flexibility to incorporate them without extensive -- meaning prohibitively expensive -- retrofitting".

He then goes on to say [15]:

"more than a few utility organizations today are faced with the problem of what to do with systems progress has rendered obsolete. Some systems cannot be expanded to meet even current needs, no less future requirements. And the list of utilities faced with this dilemma will grow within the next few years. It is essential, therefore, for a utility hoping to deal with the future to commit itself to equipment that has significant expansion capability.

This capability should encompass the installation of additional components as well as replacement of older units with newer fully compatible units that will not require changes to the program systems. Such an approach allows longer-term program activities to proceed and the computer system facilities to be upgraded to keep abreast of new computational needs. In the process, the utility's investment in program systems is protected."

V. CONCLUSIONS

In this paper we have highlighted a few of the many technical contributions that Glenn W. Stagg made to the development and widespread acceptance of digital computers in the electric utility industry both for planning studies and for operation.

We have also included some of his key insights that were ahead of their time. These have been validated and become the conventional wisdom.

This paper, together with the companion paper, which describes some of his career achievements, are the personal and professional tribute of the panel members to a giant of the industry who shaped our careers and set an example that all of us continue to follow.

VI. ACKNOWLEDGEMENTS

We appreciate that the IEEE Power Engineering Society leadership enabled us to use this opportunity to honor Glenn W. Stagg and Jorge Dopazo.

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VIII. BIOGRAPHIES

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