PERFORMANCE ASSESSMENT OF A NEW DIGITAL SUBSYSTEM FOR GENERATOR PROTECTION

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INTRODUCTION:

The protection of electric power generators against the effects of faults or other abnormal operating conditions has traditionally been accomplished by the application of separate component relays for each protection function. The majority of these relays have been either electromechanical or static analog.

The development of microprocessors and high speed memories during the decade of the 1980's made the digital technology practical for power system protection. However, unlike the electromechanical and also to some extent the static analog, the digital technology has been changing very rapidly. According to one report [1], microprocessor chips containing 100 million transistors capable of processing two billion instructions per second may be a reality by end of this decade. Just a decade ago, the original IBM PC used a 29000 transistor microprocessor chip.

The explosion that has taken place in this technology in recent years no longer affords utilities the luxury of months of engineering review, weeks of extensive laboratory testing, and extended periods of field evaluation to determine if a particular new product is acceptable for use on their system. One paper stated "the design life expectancy has shrunk from over 30 years with traditional electromechanical technology to approximately 5 years with the present rapidly changing electronic technology" [2]. With technology moving so rapidly, the evaluation steps mentioned above could easily require more time to complete than the life of the firmware version being evaluated. In order for utilities to benefit from the technology available today and manufacturers realize a timely return on their investment in a new product, a much more efficient method of evaluation and acceptance must be utilized.

One such method is an ACE TEAM or "Advisory Committee of Experts". This approach is being used for a Digital Generator Protection subsystem - DGP. The DGP relay subsystem is used throughout this paper as example to illustrate different aspects of the ACE TEAM approach.

DIGITAL GENERATOR PROTECTION SUBSYSTEM:

Background:

The application of integrated microprocessor based protection, control and monitoring subsystems in other areas such as Digital Line Protection and Distribution Protection have successfully demonstrated significant improvements in cost, performance and system operation & maintenance. However, as mentioned earlier, a majority of generator protection has remained in the form of separate component relays. Because of the cost, reliability, product evaluation, and other issues, the integration of generator protection functions using analog electronics has found only a limited acceptance in the past.

With rapidly increasing capabilities of the digital technology at decreasing hardware cost and the demonstrated reliability in other areas of power system protection, more and more utilities are willing to consider an integrated subsystem for generator protection.

As mentioned earlier, the design life of present digital protective relays has shrunk to about 5 years. Also, considerable software design effort is required for a well-engineered product (15 man-years in the case of the DLP Digital Line Protection subsystem). With limited resources and a multitude of potential development projects, innovative new approaches are necessary to develop new products of high quality in a relatively short period.

The approach used for the DGP project was to "Partner" with Hydro-Quebec of Canada. Most of the protection algorithms needed for the DGP were already developed [3,4,5,6] and field tested [7] by IREQ (Institut de recherche d'Hydro-Quebec) Laboratories of Hydro-Quebec over the last six years. A thorough evaluation of the IREQ's prototype relays (RUPA and DIGLO) was done including dynamic tests by playing back various prerecorded COMTRADE files in electronic power sources. After a successful evaluation of the prototype, licensing agreement was signed and a DGP development team was formed consisting of GE and IREQ personnel.

Functions:

For large steam, gas or hydraulic turbine driven generators the applied protection functions typically include: stator current differential, current unbalance, loss of excitation, stator ground, overvoltage, system fault backup, anti-motoring, overexcitation, over/under frequency and voltage transformer fuse failure. This frequently involves 20 or more single function component relays applied in a unique configuration to accomplish the protection, control and alarm outputs.

To optimize the cost, it was decided to integrate those protection functions in the DGP that are most commonly used. Figure 1 shows the functions incorporated along with a simplified logic diagram. These functions can be supplemented by external component relays as required. Provisions are made in the DGP to accept outputs of the external relays in order to optimize the generator system protection. The IREQ algorithms do provide many performance enhancements not previously available.

An adaptive Sampling Interval [5] maintains 12 samples/cycle for all the input analog signals over the system frequencies of 30.5 to 79.5 Hertz. This assures accurate measurements of the signals and also stable sensitivities of all the protection functions over the frequency range.

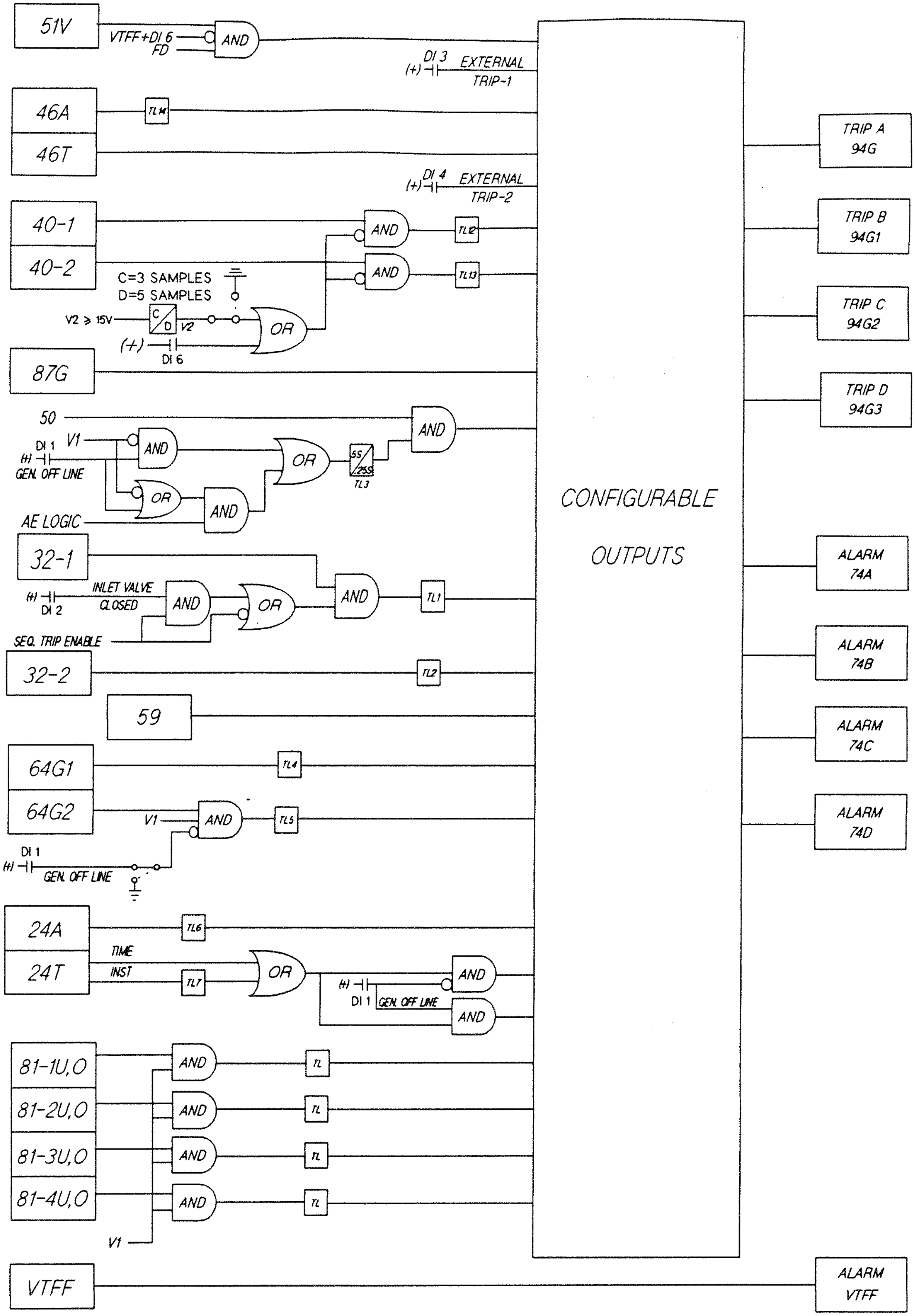

Figure 1: **Simplified Logic Diagram - DGP**

100% Stator Ground Protection is provided by two overlapping zones. First zone uses the conventional approach of neutral overvoltage which covers up to 95% of the windings. The second zone is based on distribution of third harmonic voltage at generator terminals and neutral [3]. This zone is factory set to cover 15% of neutral end of the windings providing up to 10% overlap.

Inverse Overexcitation (Volts/Hertz) characteristics of the DGP is user configurable. An additional instantaneous characteristic with settable time delay is also implemented for improved coordination with transformer and generator overexcitation capabilities.

Accidental energization protection logic is implemented in the DGP as shown in Figure 1. It should be noted that this is a complex subject and it's details are beyond the scope of this paper. The IEEE working group report [8] on this subject is an excellent reference for the many issues involved.

Configurable output relays of the DGP allows the user to assign any protection function to any number of output contacts. This facilitates implementation of the various tripping strategies used by utilities under the total ensemble of fault and abnormal operating conditions of the generation system.

Sequence of events with 1 ms resolution and Fault Report with programmable oscillography of the analog input waveforms help in analysis after a trip event. The time tag clock can be synchronized to a standard time by a demodulated IRIG-B signal or a signal from a G-NET system. G-NET is a protection and control integration system for interfacing with Intelligent Electronic Devices (IED's).

Design Approaches and Implementation:

The toughest challenge for the DGP team was to develop a relay that would meet GE quality in a very short period. Also, a hardware platform design that was consistent with other GE digital relays and which would allow porting of the proven IREQ software with minimum changes, were important goals. These goals would more quickly result in a high quality product that is easier to manufacture at a reduced cost to the end user.

The obvious choice for the hardware platform was the one based on GE's DLP protection subsystem. This platform was well suited to implement the IREQ protection software without major changes. Several of the DLP hardware modules were suitable for the DGP without any changes. These include system processor, data acquisition processor, man machine interface, and the power supply modules. Among the modules specifically designed for the DGP is a Digital Signal Processor (DSP) module. This multi-DSP module with a four port memory has enough processing power for the present functions as well as future enhancements of the DGP. As the requirement for analog signal processing was very different compared to the one used in DLP, a new analog front end module was also designed.

By maximizing the implementation of existing proven hardware with either no or minimum changes, a reliable hardware platform was obtained with minimum effort. Figure 2 shows a simplified architectural block diagram of the relay. Similar techniques were used in packaging by utilizing the standard GE modular design.

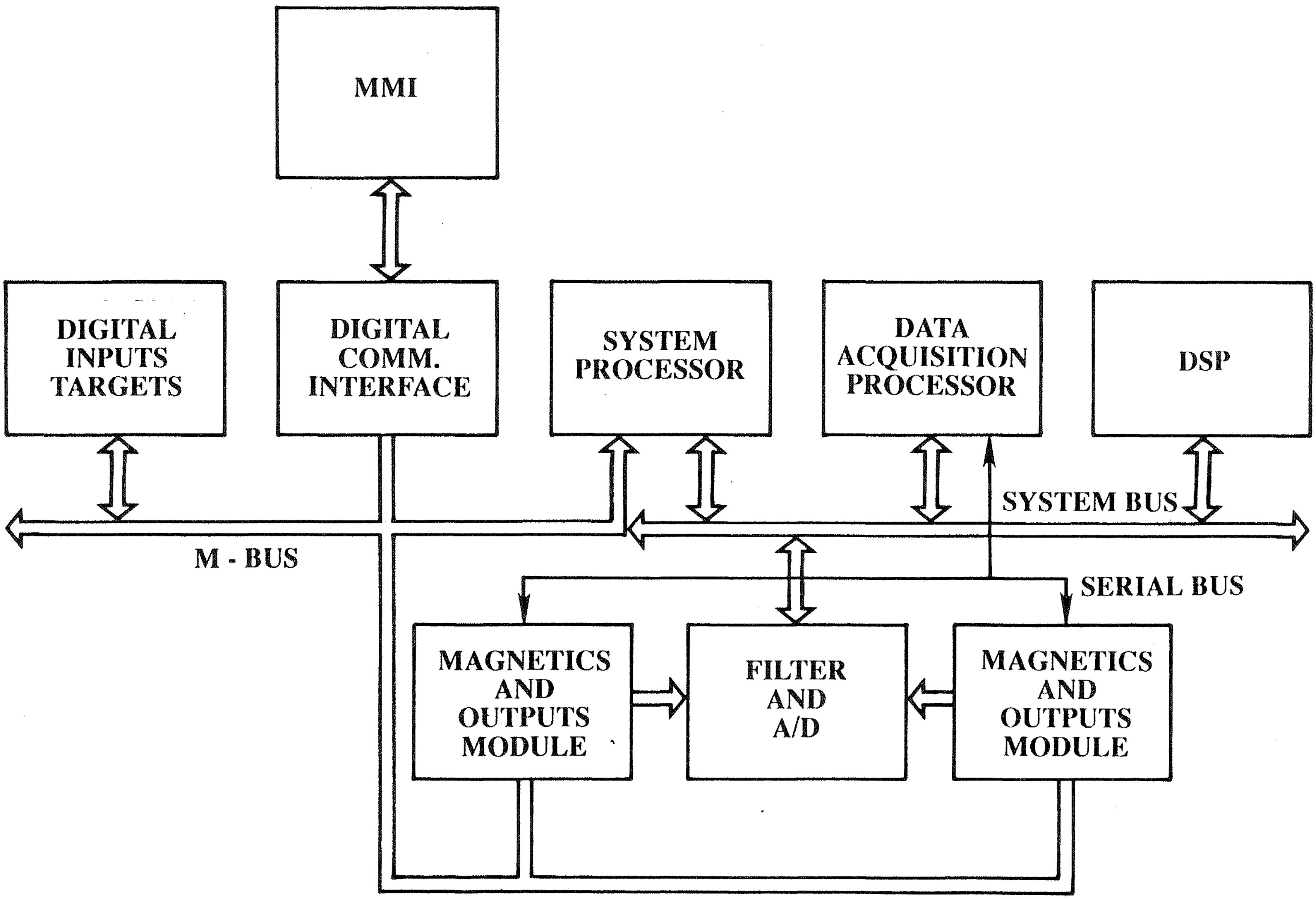

Figure 2: **Simplified Architectural Block Diagram - DGP**

Like the hardware platform design, every effort was made not to "re-invent the wheel" for the software development. A number of DLP software "blocks" like man machine interface (MMI), communications, and self-tests were implemented on the DGP platform with minimum changes. Such multiple use of the existing software across a product line saves development time, provides software which is field proven, and the end user can potentially save a considerable time in the field. In the area of DSP software, utmost care was taken not to change any part of the software that did not require changes to take full advantage of various tests performed in the past. A step by step approach was taken to integrate the protection algorithms into the DGP.

As a first step, IREQ software for three selected protection functions were implemented in a modified DLP relay. This verified the transportability of the IREQ software to the proposed DGP platform at an early stage of the development. Next a detailed software functional specification was generated and the proposed hardware design was firmed up. When the DGP hardware became available, the same three functions were implemented first on this new platform and thorough tests were performed. Additional functions were implemented in each of the next several steps with a thorough testing along the way to verify the performance.

Reliability:

An integrated protection subsystem offers economic, functional and physical size advantages as mentioned earlier. Also it raises the issue of reliability. The Reliability assessment using MIL Handbook 217E for the DGP hardware platform indicates a rate of 0.07361 failures per year. It is estimated that 75% of these failures can be detected by self-test. Thus the predicted operational failure rate is one fourth as much, or 0.0184 failures per year. This rate goes down to 0.0169 per year if the optional backup power supply is used. The real issue is not these very low predicted hardware failure rates, but the consequences of any failure, no matter how unlikely, in an integrated protection subsystem.

Although the highest reliability clearly results from the application of a redundant generator protection subsystem, it is reasonable to expect that there will be applications where other considerations will preclude this. Accordingly, a high degree of redundancy is engineered into the DGP to minimize single contingency failures of the protection subsystem. These include optional dual DC power supplies and multiple processors.

The extensive self test and diagnostic software significantly reduces the possibility of either a false operation or the failure to respond to an abnormal condition, because of the immediate detection and alarming of any DGP hardware problem. The logging of any setting or configuration changes and alarming of repetitive unsuccessful access attempts enhance the overall reliability of the DGP.

Design Assessment:

Due to the requirement for high reliability, dependability, and security of the protection function, manufacturers and utilities alike place a high premium on the functional and operational testing of relays. Traditional assessment procedures entail type testing of a prototype both on the bench and on a power system simulator. Operational testing typically includes board level testing and final system test. Once sold to a utility, performance assessment often continues with additional bench testing and "On Line" assessment for a period of a time. The DGP protection subsystem brings with it extremely high requirements in the performance area (due to the consequences of a misoperation) and offers some challenges both in the area of type testing and operational assessment.

DESIGN ASSESSMENT METHODS:

To meet the challenges of the DGP certification, a total program concept was established to focus on all aspects of testing. The program consists of a five pronged approach, namely, bench testing, analog simulator testing, digital simulator testing, enhanced production testing, and customer testing.

Bench Testing:

As modules of software and hardware are developed, the design engineer will test the module with effective steady state signals allowing assessment of algorithm performance and sensitivity. As the DGP has some complex test configurations like injecting various ratios of third harmonic voltages, bench testing has turned to computerized waveform generation. Signal patterns are stored and recalled when needed allowing for rapid algorithm adjustment and re-test.

Analog Simulator - System Description:

Clearly, the most demanding part of the test program is verification of the dynamic performance of the DGP. Traditional analog simulators have focused on the modeling of static elements such as transmission lines and transformers for the testing of their associated protection equipment. The power generator, being a rotating piece of equipment, has complex dynamic interactions between the prime mover, generator controls, and the power system over a wide range of operating conditions. For completeness, dynamic testing of the DGP requires an accurate model on which to exercise the relay over the ensemble of possible operating conditions.

Physical scale models of two 907MVA and a 1444MVA cross compound generator and interfacing transformer and line models were developed in the early 1970's in a joint venture between the MIT Electric Power Systems Engineering Laboratory and the American Electric Power Service Corporation. The models were originally built due to concerns over lack of field data in this area as well as a need to verify computer models used in large system studies. The system has demonstrable characteristics and controls that are similar to actual field systems. The 1444MVA model was acquired for the purposes of dynamic DGP testing and is shown in figure 3.

The 1444 MVA model was built to one millionth scale and as such, each half of the cross compound unit is rated for about 700VA with a 221V output rating [9]. On a scaled basis, the model is "electrically correct" - carefully modeling the per unit reactances, actual time constants, and rotor inertia. Included in the

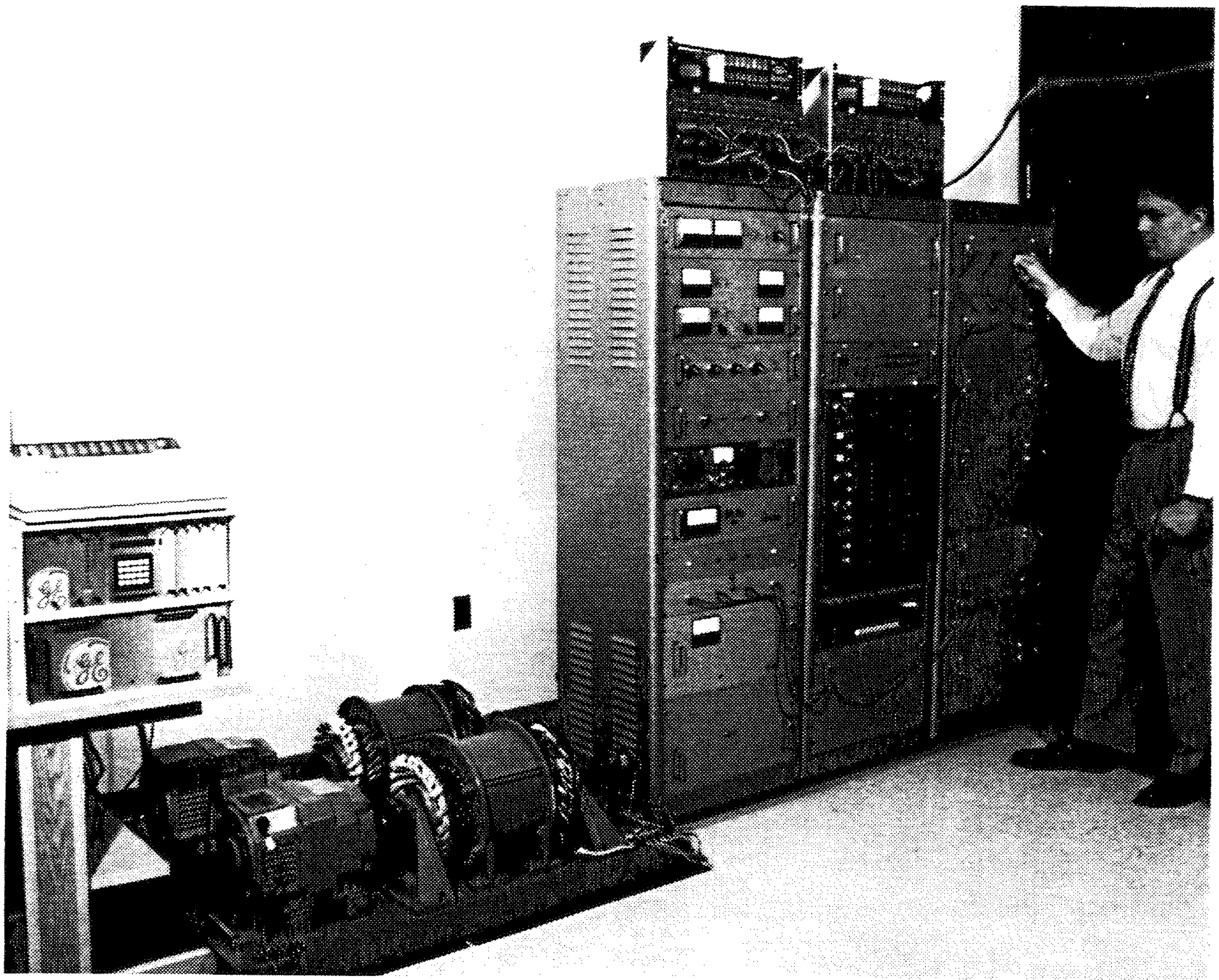

Figure 3: **Model Generators and Associated Controls**

overall control system are operational amplifier models of a supercritical steam generator with three time constants and appropriate transfer functions and gains to simulate governor dynamics and droop. Figure 4 shows the block diagram of this control system.

The machines are hand wound and give access to all stator terminals as well as limited access to intermediate points on the stator winding. High impedance grounding is effected by an equivalently sized resistor located between the generator neutral and ground. For synchronized operation, the unit can be paralleled with the local utility. As the design is extremely robust, it can be subjected to a wide range of faults and system operating scenarios with relative impunity. Various fault types, fault locations, and fault initiation angles can be effected, consistently repeated, digitized, and stored on optical disk for future reference. Since the full load currents are about 1.8 amps, 2.5:5.0 amps current transformers were installed to bring the steady state currents closer to typical field conditions. Figure 5 shows a one line of the test system as implemented. The system can test for virtually any generator abnormality, for example, Stator Differential, Stator Ground, Loss of Field, Overexcitation, Over/Under Frequency, Reverse Power, etcetera.

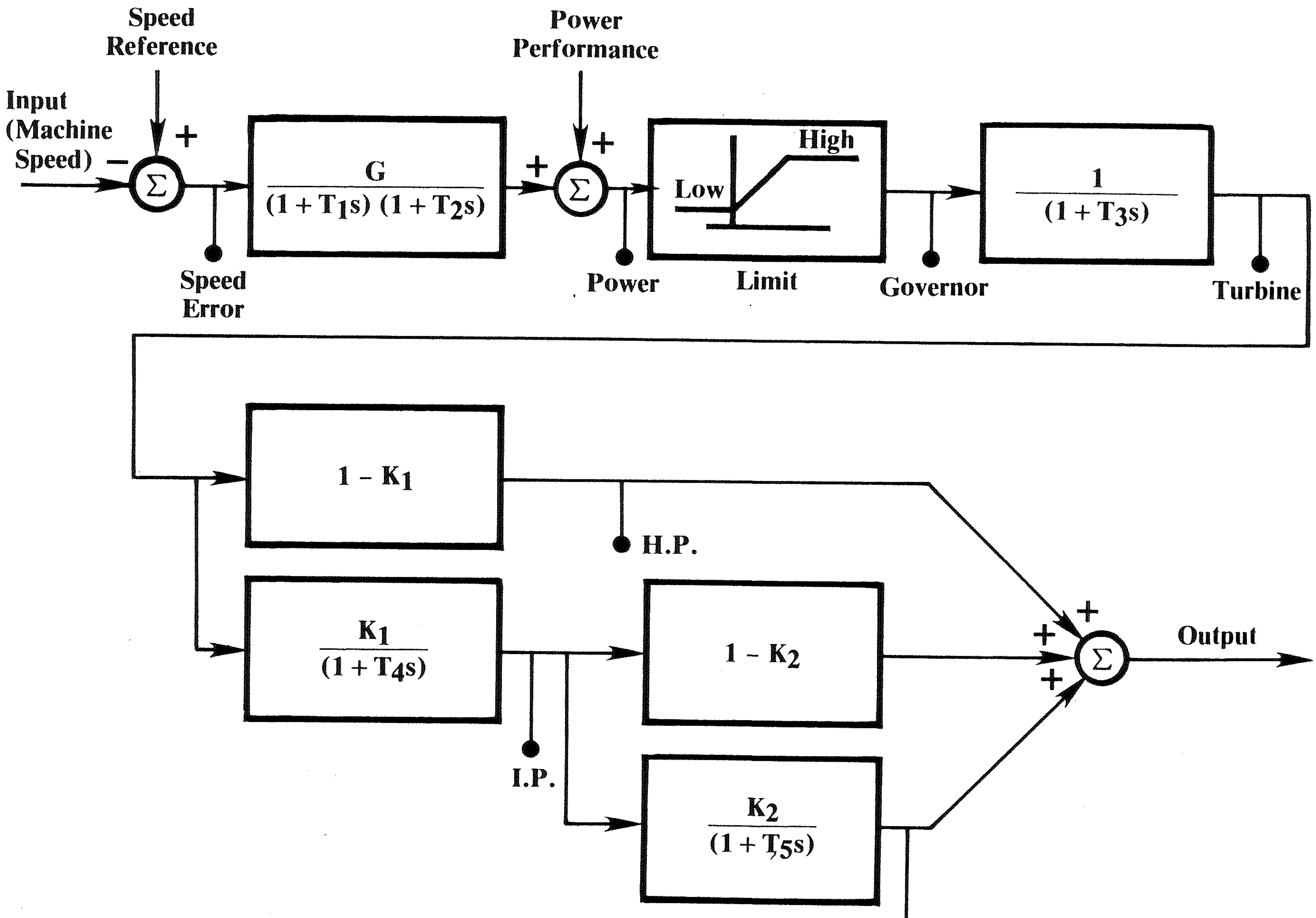

Figure 4: **Equivalent Steam Turbine-Generator Block Diagram**

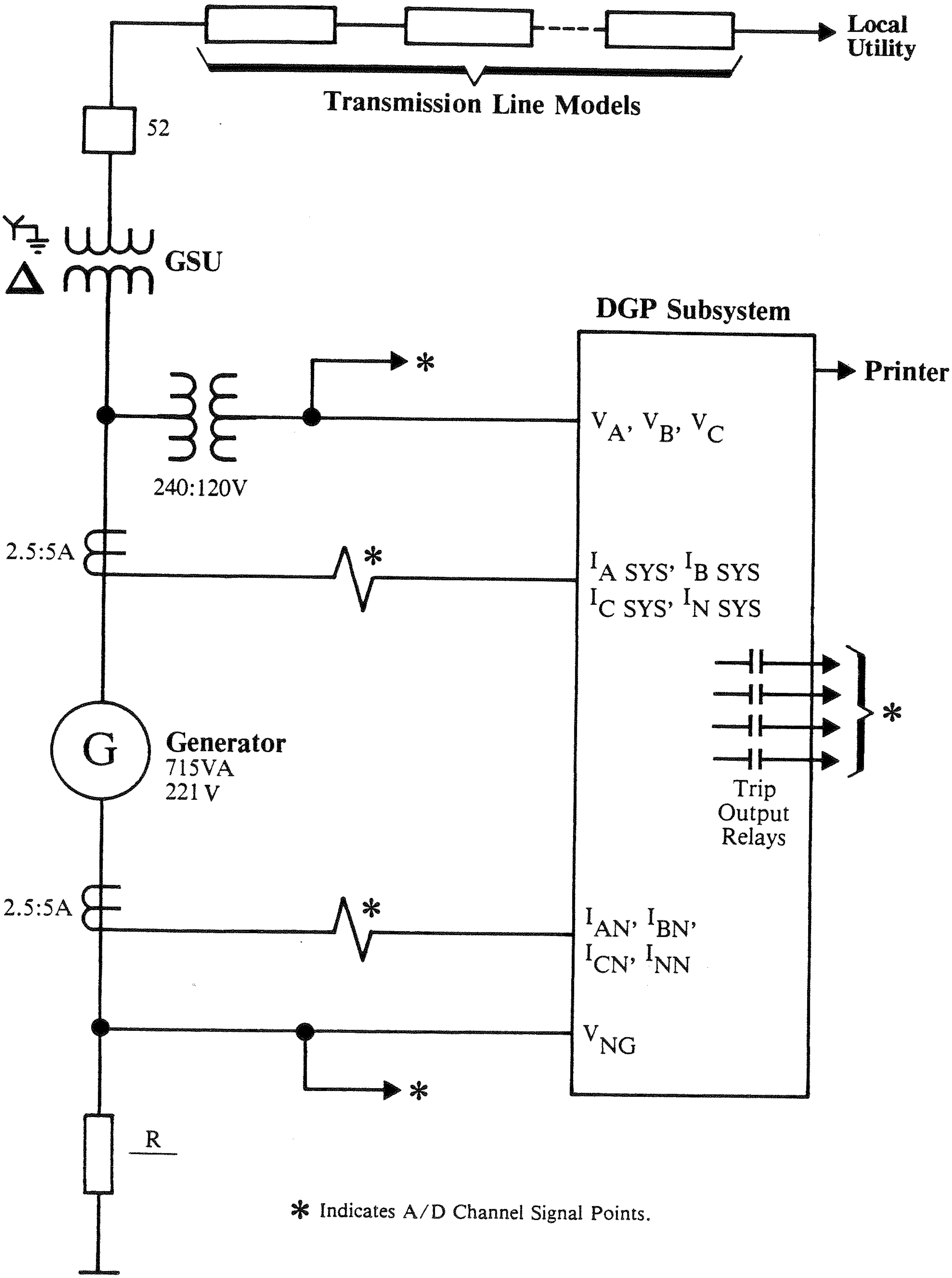

Figure 5: **Generator Test Configuration One-Line Diagram**

One of the more uniquely modeled aspects of the system is the excitation system and field winding. On an actual generator, the L/R ratio of the field winding is quite large yielding a time constant on the order of 5 seconds on Loss of Field. As the rotor of the models electrically falls short of this number, equivalent time constants are achieved by electronically providing a "negative resistance" in the field supply. In the actual implementation, the time constant, T'_{do} is adjustable over a wide range of times. As such, the DGP Loss of Field protection performance can accurately be tested for a range of machine time constants.

Analog Simulator - Test Results:

Almost 1000 test cases were run on the Analog Simulator covering the gamut of protection functions contained within the DGP. Through this testing, the relay design was fine tuned for optimal security and dependability under dynamic operation conditions. Characteristic test cases were digitized along with the relay responses and archived on Optical disk. Two examples of the stored test cases are illustrated in figures 6 and 7.

Figure 6 is an internal 3-Phase Generator terminal fault showing the Phase A currents at both the system and neutral sides of the generator. Clearly visible is the transient response of the machine including the DC offset and subsequent DC decrement. The 87G "trip" output (CH12) of the relay is superimposed on the currents allowing for easy viewing of the relay response.

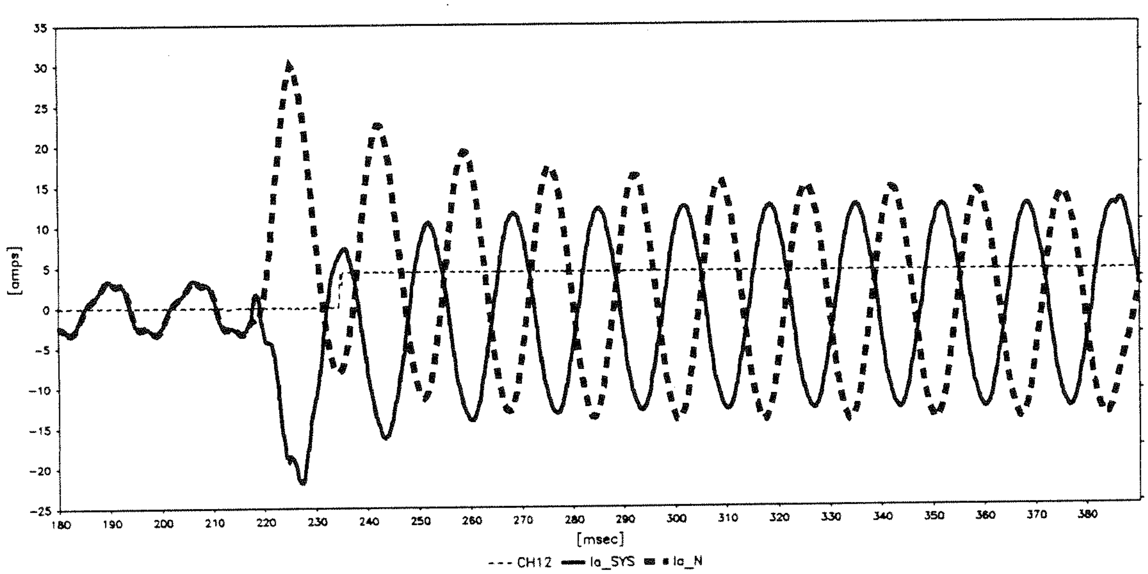

Figure 6: Phase-A current waveforms for 87G trip test
(File: 5J5M52D)

Figure 7 is a dynamic R-X diagram showing the locus of machine terminal impedance traversed during a Loss Of Field (LOF) condition. The impedances were obtained via ratios of Fourier Transforms of the Voltages and Currents and then plotted in 0.05 second increments (shown by the circle markers in the figure). The trajectory takes the impedance from load to within the 40-1 LOF characteristic.

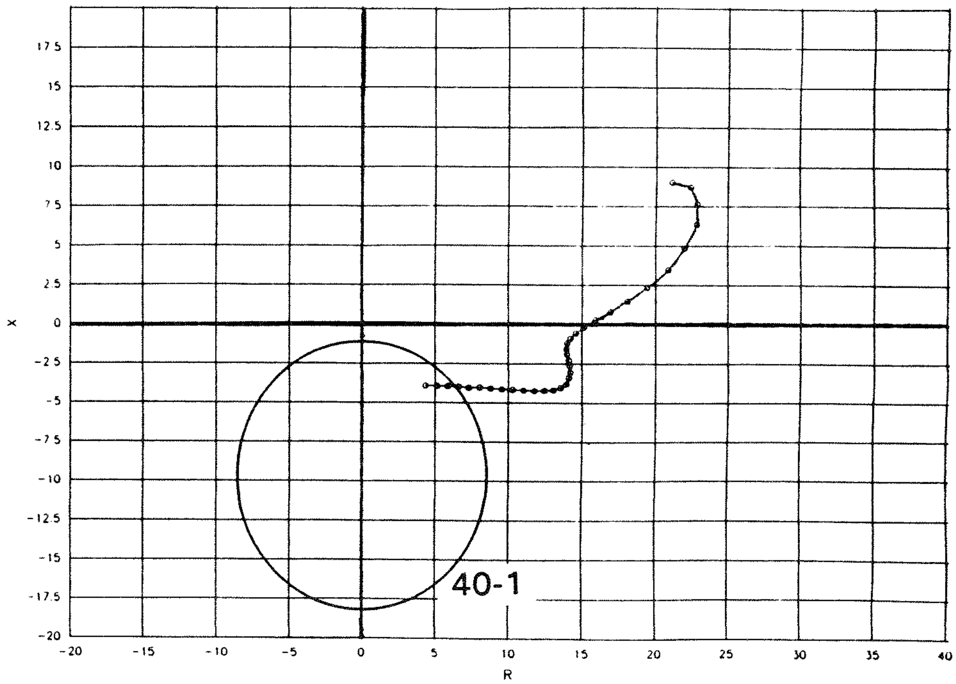

Figure 7: Dynamic R-X diagram for Loss Of Field case
(File: LXOM63X)

Digital Simulator Testing:

A testing technique that has recently become available is that of playing digitized data through D/A converters, into hi-power amplifiers, and into the relay under test [10]. At P&C Technology Center in Malvern, PA, such a facility exists with a 24 channel capability, 30 kHz per channel synchronized output data rate, and a total power availability 75kVA. Sources of dynamic test data include EMTP simulations, Analog tape recorders, and Digital Fault Recorders (DFR). Test cases created from EMTP fault studies include internal phase-phase fault, external unbalance fault and loss of excitation conditions. Actual Generator operating cases like loss of excitation and static start operation captured by DFR's are also available along with several through fault cases captured at the GE Skeats High Power Laboratories. As testing with the analog machine models progresses, the analog values are being digitized and a database of test cases is being compiled. With the evolution of the DGP system, the unit will be able to be automatically re-tested by playback of the database through the relay. As the concept of playback evolves, special cases of concern to a customer could be sent to the manufacturer allowing for a "personalized" test program.

Production Testing:

Due to the criticalness of performance of the DGP, production testing is being enhanced in two areas to build a higher degree of confidence in the shipped product. First in the area of hardware reliability, the unit is temperature cycled under power for 24 hours to weed out any infant mortality. Secondly, traditional steady state performance assessment is being augmented with dynamic testing capability on the production floor. A scaled down analog playback system will be available to play selected critical test cases to verify the relay responses.

ACE TEAM:

The last phase of the DGP test program is customer participation at various stages of the development process using the ACE TEAM (Advisory Committee of Experts) concept. This approach provides the end user, an efficient method of evaluation and acceptance of new product with a high degree of confidence in a timely manner consistent with the rapidly changing technology.

This concept draws on competent personnel from many different utilities and engineering firms. Team personnel are involved at the conceptual design stage of a new product. Their expertise in the designated area helps focus the product on the real issues that need to be addressed. The process also assures that the new product has the capability to address unique application requirements. This committee has input regarding system functionality and philosophies to be included in the new product. This partnership between the manufacturer and the end users assures a product that will be better received in the beginning and require fewer revisions and modifications to appeal to the market. The interaction of the ACE TEAM also tends to galvanize the expectations of the group such that all members will share a perception of the capabilities of the end product.

Accelerated Design Testing:

For each utility to perform an independent laboratory evaluation of the entire functional capability of the product is time consuming and involves much repetition between utilities. The ACE TEAM concept encourages all members to participate in the manufacturer's testing program and share the results. Utilities benefit by taking advantage of Manufacturer's sophisticated test equipment such as model generators, model power systems, and digital fault simulators which are not available to the Utilities without great effort and expense. Each member is offered the opportunity to have input into the type testing to be performed as well as to furnish specific test cases. These specific cases can be furnished in either a digital or an analog tape format to the manufacturer and be used in digital fault simulators to conduct tests. Members of the ACE TEAM are invited to witness these tests. Members witnessing tests and concurring with the results should negate the need to duplicate these tests by each individual utility. Certainly some laboratory testing will be performed by the purchaser. This is normally required to familiarize the user with the device, and to provide some training to the personnel required to install, test, and check out the device. Overall this approach should vastly reduce the amount of man-hours currently being expended by all utilities doing evaluation testing.

Accelerated Field Evaluation:

An important part of the ACE TEAM philosophy is the sharing or partnership during the field evaluation period. All utilities normally require some period of field evaluation. These field evaluations are normally conducted with the device receiving input quantities, alarms connected, and trip outputs disconnected or connected to alarm only. The length of this stage of the evaluation varies among utilities and complexity of the devices. By using the ACE TEAM concept a relatively small number of field evaluations can be conducted utilizing utilities with different types of systems, sizes of machines, or operating conditions. The data obtained is then shared by all members of the ACE TEAM allowing each to benefit from several "relay months" of experience on different systems and under varied conditions. This approach allows many utilities to receive the information gained from field evaluations without each conducting separate field evaluations.

In the business world today all of our companies, whether manufacturer, utility, or engineering firm, are being required to cut back, do more with less, and work smarter. The ACE TEAM approach is compatible with these objectives. By forming a partnership between the groups, common goals can be achieved while reducing time required to evaluate and accept new technology. This can be accomplished with fewer man-hours expended while allowing the utilities to take advantage of newer technology sooner with more comprehensive evaluation data.

CONCLUSION:

For the critical function of Generator protection, many utilities tend to take more conservative approach than for protection of some other areas of the power system. In general, performance assessment of new digital protective relays using traditional approaches can potentially take longer than the design life of the new relay. To effectively take advantage of digital technology, new methods of relay development and performance assessment are required.

Shared hardware and software, physical scale models, digital simulator, library of digitized data obtained from sources like EMTP studies and DFRs are important components of these methods at the design and verification stages of the relay. In addition to these, the ACE TEAM concept provides a vehicle for sharing performance experiences to accelerate the acceptance process in a timely and cost effective manner.

REFERENCES

1. M. G. Adamiak, R. C. Patterson, "Communications Requirements for Protection & Control in the 1990's", GE Publication GER-3677.

2. C. R. Heising, R. C. Patterson, E. Y. Weintraub, "Digital Relay Software Quality", GE Publication GER-3660.

3. G. Benmouyal, "Design of a Universal Protection Relay for Synchronous Generators", CIGRE session 1988, No. 34-09.

4. G. Benmouyal, "Some Aspects of the Digital Implementation of Protection Time Functions", IEEE PES Winter Meeting, Atlanta, GA, 1990.

5. G. Benmouyal, "An Adaptive Sampling Interval Generator for Digital Relaying", IEEE Transactions on PD, Vol. 4, No. 3, July 1989.

6. G. Benmouyal, "Design of a Combined Digital Global Differential and Volt/Hertz Relay for Step-Up Transformers", submitted to the IEEE PES Winter Meeting, 1991.

7. G. Benmouyal, S. Barceloux, R. Pelletier, "Field Experience with a Digital Relay for Synchronous Generators", IEEE PES Summer Meeting, Los Angeles, CA, 1989.

8. IEEE Working Group Report No. 88 SM 527-4, "Inadvertent Energizing Protection of Synchronous Generators".

9. S. D. Umans, G. L. Wilson, "Physical Scale Model of a Power System - A User's Guide", Massachusetts Institute of Technology Report No. 43, December 1973.

10. M. G. Adamiak, G. E. Alexander, J. G. Andrichak, "Power System Simulation: A High Power Amplifier Approach", Georgia Tech Protective Relay Conference, April 29-May 1, 1992.

BIOGRAPHIES

Mark Adamiak received his BS and ME degree from Cornell University in Electrical Engineering in 1975 and 1976 respectively and his MS-EE degree in 1983 from the Polytechnic Institute of New York. Mark joined the System Protection and Control section of American Electric Power (AEP) upon graduation in 1976. While at AEP, his attentions were focused on the use of Microprocessor based systems for the protection, control, and monitoring of power systems. In August of 1990, Mark joined General Electric's Meter and Control Department in Malvern, Pennsylvania as Manager of Advanced Technology Programs. He is presently responsible for product planning and for identifying new technology for the protection community. In 1986, Mark was the winner of the Eta Kappa Nu (HKN) society's "Outstanding Young Electrical Engineer" award. Mark is a member of HKN and IEEE and is a registered Professional Engineer in the State of Ohio.

Dhruba P. Das received his B. Sc. in Electronics Engineering and M. Tech in Electronic Instrumentation from Institute of Technology, Banaras, India in 1973 & 1975 respectively. After graduation he taught at Assam Engineering college before coming to the U.S.A. He earned his M. Sc. in Electrical & Computer Engineering from University of Wisconsin, Madison in 1979. Dhruba has been working with GE since August of 1979 and held various positions. He is currently a senior development engineer and program manager for the DGP relay.

Jonathan D. Gardell received his BS (EE) degree from Worcester Polytechnic Institute in 1981. He worked for the American Electric Power Service Corporation for nine years mainly in the area of major electrical equipment. In 1987 he received a MS (EE) degree from The Ohio State University. Since July 1990 he has been working as a Senior Application Engineer in GE's Power System Engineering Department. He is a Member of the IEEE Power Engineering Society and active in the Power System Relay Committee.

Subhash C. Patel received his BS (EE) and BS (ME) degrees from the M. S. University, Baroda, India in 1965 & 1966 respectively. He worked for Brown Boveri Company in India before coming to the U.S.A. in late 1967. He received the MS (EE) Degree from the University of Missouri - Rolla in 1969 and joined Illinois Power Company in Decatur, Illinois where he was primarily responsible for power system protection. Since 1979, Mr. Patel has been with GE and has had various assignments in the field of protection and control as well as gas turbine package power plants. He is currently a senior application engineer in GE P&C Technology Center at Malvern, PA. Mr. Patel is a senior member of IEEE and a registered professional engineer in the states of Illinois and New Hampshire.

David L. Viers received an AS degree in Electrical Technology from West Virginia Institute of Technology in May 1965. He was employed by Virginia Power in 1965 in the Automation and Control Department. He has held various positions including Field Supervisor Control Operations, Supervisor System Protection, and is presently Senior Staff Engineer in System Protection Generation responsible for generation protection design standards and protection requirements for power station projects. He is also an Associate Member of the Pennsylvania Electric Association Relay Committee.