EDWIN L. HARDER

Figure 1. Edwin L. Harder, power engineer, inventor, builder of the Anacom computer, former president of the American Federation of Information Processing Societies, and current resident of Pittsburgh, Pennsylvania.

CHAPTER
6

Calculating Power
Edwin L. Harder and Analog Computing in the Electric Power Industry

In today's marketplace, laptop computers can move from a market leadership position to obsolescence within a few months. In even the most staid sectors of the computer industry, manufacturers replace their product lines with more competitive products every several years, and one has to look hard to find a company using computers built before 1980. A leading historian of computing has called the first digital computers, built in the late 1940s and 1950s, "dinosaurs"—a description that accurately conjures up images of enormous masses, too slow and cumbersome to survive in a modern environment.[1] It is truly remarkable, then, that in 1990 a general-purpose computer built in 1948 was still in operation at a leading engineering firm in the United States.[2]

This paper describes this computer, the Anacom, and the man who built it and managed its operation for two decades, Edwin L. Harder.[3] Although Harder characterized the Anacom as his top achievement, in the twenty years prior to building this machine he had already distinguished himself as an engineer in the electric power industry. This career led him directly into a leadership position in the computer field. Harder was the author of numerous inventions in his early career, and several of his patents helped to keep his employer, Westinghouse Electric Company, solvent in the depths of the Great Depression. His influence extended beyond his company to the wider professional community through his distinguished service in national and international professional organizations.

Early Life and Education

Edwin L. Harder was born on April 28, 1905, in Buffalo, New York, to Edwin P. and Cordelia Mandana Cousins Harder, the second of five children. His father, having been one of the first to receive an electrical engineering degree from Pennsylvania State University, was superintendent of the distribution substations of the Cataract Power and Conduit Company in Buffalo, which later was consolidated into the Buffalo General Electric Company.[4] As the only college-educated employee, he was on constant call to preside over problems with the Buffalo power network. Harder's mother held various professional jobs, including nurse and teacher, and once worked as a secretary at General Electric. She met her husband while nursing him to recovery from burns received in a manhole fire.

Harder had an active, middle-class childhood. As an adolescent, he worked weekends in the local fruit market. His hobbies included bicycling, roller and ice skating, and raising rabbits and pigeons. He built his own ham radio rig, except for the expensive earphone, which he borrowed from a friendly telephone repairman. His high school, Lafayette, was the best scholastic preparatory school in Buffalo, and he excelled in his studies there. He showed an interest in his father's profession at an early age, and as a high school junior he worked one summer in the meter department at Buffalo General Electric to gain first-hand experience of electrical engineering.

Harder matriculated at Cornell University in the fall of 1922. His father wanted him to attend Penn State, but a four-year, land-grant scholarship to Cornell decided the matter. After giving serious consideration to mechanical engineering, Harder majored in electrical engineering.[5] Cornell had one of the top programs in the country. As preparation to work in industry, engineering students received hands-on training in foundry, forging, woodworking, machine shop, and mechanical drawing. There were three years of physics (including electricity) and chemistry instruction, and an unusually heavy dose of mathematics including differential equations and Heaviside's operational calculus. Electrical engineering courses began with DC circuits and resistors and proceeded to AC circuits. Extensive laboratory work was part of both mechanical and electrical engineering study. Harder took particular inspiration from the teachings of Vladimir Karapetoff.

Although Harder remembers devoting many hours to chess playing and other idle pursuits during college, he compiled an excellent academic record. He was one of a very few students elected to all three honor societies: Phi Kappa Phi, Eta Kappa Nu, and Tau Beta Pi. When he graduated in 1926, the economy was booming, jobs were abundant, and he received several job offers. He selected Westinghouse, where several of his friends from Cornell had accepted jobs and where he believed he would have the greatest opportunity to choose his line of work because of the large number of engineers the company hired each year.

Electric Utility Engineer

Harder was one of about 300 new engineers hired by Westinghouse that year. All new engineering hires were subjected to a year of in-house training. About 100 of these trainees went into engineering, the rest into sales. All of them spent a month or two in each of several departments: building switchboards and wiring circuits in the shop, doing elementary tasks in the design of motors in the motor engineering department, testing big machines, and working in the department that made electrical insulators. For those entering into engineering, the training also included a rigorous three-month engineering school, in which the principal engineers from different departments gave lectures on practical and theoretical subjects. The courses were rigorous enough that the University of Pittsburgh gave graduate credit for them. By taking several additional courses, Harder was able to earn a master's degree in electrical engineering there in 1931.

I have an interesting story about my Master's thesis. Pitt has a catalog out that tells the requirements of getting a master's degree or a doctor's degree. And it says plainly that the thesis has to be published. So I get this problem of DC in transformers. First time it's ever happened. Beautiful thesis project! All this was brand new information. Nobody knew anything about it before then, and so I made tests, found out how it worked, and wrote it up and published it. Took it down to Pitt and— "Oh, no! It doesn't mean that. We have to approve the thesis before you start working on it. You can't use that for a thesis." "Why?" I said, "the book says it has to be published." "Well, it doesn't mean that. We have to approve it first." So then I came on this saturating reactor problem, and I did get it approved . . . that I could write the thesis on this subject. I happened to be down in Professor Dyche's office one day, and I said, "Well, it's coming along fine. It's going to be published in the Electric Journal. *It's going to be published in March." I was probably down there in November or December. Dyche almost blew up. He said, "Well, you can't publish that." I said, "The book says it has to be published." He said, "Well, it doesn't mean that. What it means is that* **we** *publish it." And so we called Charlie Scarlott, who was the editor of the* Electric Journal, *and Charlie* *agreed to delay it for several months before he published it so that I could add a footnote that this is based on a thesis presented at the University of Pittsburgh. So he published it, after the thesis was accepted. He was a good friend, and he delayed it. So that's the story of how this finally became my master's thesis. But it also was a good subject because it was something that had never been run into before and had a lot of good theory connected with it.*[6]

Harder's mathematical training at Cornell helped to set him apart from the other new recruits. In one of the in-house courses, he caught the attention of an instructor by being able to derive mathematically the equations of traveling waves on transmission lines. This helped him to secure a position in the General Engineering Department, which worked on systems problems, mainly consulting for customers with difficult technical problems that occurred in the application of electrical equipment to their systems.[7] All General Engineering employees began by working for two years in one of the design engineering departments in order to get to know a particular kind of equipment manufactured by the company. Harder was assigned to the electrical development section of the Power Engineering Department, which built large rotating equipment.

Although Power Engineering was ostensibly a good place to learn about the company's large rotating machines, Harder's section head was totally immersed in a problem relating to air flow and ventilation of machines, and Harder was assigned nothing but these kinds of problems to work on. His experience here was no doubt narrower than the company policy intended, but it taught him about dimensional analysis in models, which he later put to good use in his computing work. While working in Power Engineering, he made his first significant contribution to the company by constructing a hot-sphere anemometer, a device conceived by one of his fellow engineers, which was inserted through the bolt hole of a machine to measure the internal air velocity.

By accident, Harder was able to return to General Engineering before his two years were up. Power Engineering laid him off during a company downsizing, but just at that time a position became available when someone left General Engineering after it had already made its required personnel cuts. Harder was assigned to railroad electrification—a fortuitous assignment because it enabled him to remain employed during the Depression. The Pennsylvania Railroad undertook a major program to electrify its lines from Philadelphia to West Chester, Trenton, New Brunswick, New York City, Washington, and Harrisburg during the Depression. In the darkest days of the 1930s, the railroad's president, General Atterbury, ordered ten million dollars worth of electric locomotives from Westinghouse. This order helped to keep the East Pittsburgh plant open and Harder employed.[8]

Harder was attracted to General Engineering because it concentrated on systems work rather than on the design of specific equipment. The prevailing characteristic of his work there, however, was extensive calculation, including the use of (digital) desk calculators and various special-purpose analog devices built by the company. In college Harder had never used a calculating tool other than a slide rule. But in General Engineering he soon became responsible for using an electrically powered Marchant desk calculator to make extensive calculations on the engineering design for the electrification of the Pennsylvania Railroad.[9] Another project, which investigated rectifiers used in the power transmission system that were causing telephone interference, required him to use a Chubb mechanical harmonic analyzer, a device similar to a planimeter that was moved mechanically around a cutout of a polar oscillogram to determine the rectifiers' harmonics.[10] Based upon these calculations, he designed AC and DC filters to reduce the harmonics to a level at which they no longer caused serious interference.[11]

From 1938 until 1946, I was assigned to the Middle Atlantic District, including Washington, D.C., as a sponsor engineer. In the latter part of that period, we were visiting the Potomac Edison Company, which is headquartered in Hagerstown, Maryland. It's a system about 100 miles wide, maybe from Cumberland to Fredericksburg [Maryland], about 50 miles north-south from the Pennsylvania Turnpike down into West Virginia. Their headquarters was in Hagerstown, and the salesmen from Philadelphia would take me down there occasionally. They had one good technical man, and they had an older manager who had previously run the streetcar system from Pittsburgh to Butler [Pennsylvania]. He did a commendable job, but they were having a very unusual problem; at nights and [during other] light-load periods the whole outskirts of their system would have a very high fifth-harmonic voltage content. It would get 10 or 15 percent fifth-harmonic voltage. On a capacitor, 100 percent of 60-cycle voltage will produce 100 percent current, but it only takes 20 percent of fifth harmonic to produce 100 percent current because the impedance of the capacitor is only one fifth as much. The older capacitors did not have enough reserve in them to handle that much extra current, and consequently they were failing. Also, switchboards were burning up due to excessive currents in switches.

They took me up to the Pennsylvania Turnpike and showed me some of these stations where the switches were all blistered. They were very confused. As I told you before, I had had a lot of experience with harmonics. I knew harmonics better probably than anybody because I had had this dual experience of telephone interference and building filters and teaching harmonics, and the Pennsylvania Railroad's problem with harmonics. They didn't have any rectifiers and the only source of harmonics is the transformers. If a transformer has to produce a sine-wave voltage, it has to have a sine-wave of flux. And the exciting current is not going to be sine-wave. It's going to have a lot of harmonics in it. I knew a couple of different equivalent circuits of transformers that correctly represented them. I knew that up at Sharon we had used several kinds *of iron in transformers. Just from the characteristic of the iron, I could calculate what these harmonics would be. It wasn't too different for any of these five different kinds of iron they used. I assumed that GE's iron must be about the same and that this equivalent circuit would probably work for all transformers.*

So I set up the whole Potomac Edison system on the AC calculating board at 300 cycles (i.e., at fifth harmonic). I started with the equivalent circuits of the transformers which is where the harmonics were coming from. I represented all the loads, mostly guessing at them. The starting current of a motor might be five times normal. Well, that's when the slip is 100 percent, when the motor is standing still. The fifth harmonic is the same. So motor load is roughly 20 percent impedance at the fifth harmonic. I guessed at how much was lighting and static loads, and how much was motors, and I put the loads at all of these stations. Then I ran it on the calculating board, which showed that they were right at the peak of a resonance. If you added capacitors to the system you passed the resonance point.

So I told them that if they would install a 2,000 kVA capacitor at Winchester, Virginia, it would solve all their problems. Nobody had ever done this before or has done it since, so far as I know. A 2,000 kVA capacitor was at least ten times bigger than anything they had ever installed before in the way of a capacitor. They had installed 100 or maybe 200, but not 2,000 kVA. So they asked GE about it, and GE wrote them a letter stating that it wouldn't work and recommending against it.

But the technical engineer there was a radio ham, too, and knew a lot about electricity. He knew enough that he could go to a station and filter out the fifth harmonic and put it in an oscillograph and measure it. He could get the right circuits set up so that with an ordinary oscillograph he could take a picture of what the fifth harmonic was. He saw my calculations and asked why I concluded this. He believed my reasoning, and they installed the 2,000 kVA capacitor at Winchester. There were tests, and it did exactly what I said it would do.

I had told them if they put a coil—a reactor—in series with this capacitor and tune it to the fifth harmonic, the current that it will draw will be within its capacity. I had measured on the calculating board how much this current would be, and there wasn't too much. They could actually tune it, so they called it a filter. They put this capacitor on, and they got the benefit of it for power factor correction. It actually short-circuited the fifth harmonic at Winchester. And at Frederick, 50 miles away, it brought it down to half. There was a fellow from the telephone company there to witness the test, and he wrote me after he retired he had been so impressed by that test; nobody had ever tried it before. I wouldn't have tried it if I hadn't had all that experience with harmonics. And I had confidence in my calculations. [12]

During this period Harder also did some important calculations for the company on the effect of lightning strokes on transmission lines. One of

Westinghouse's chief engineers, C. L. Fortescue, had determined that only direct lightning strikes cause damage to transmission lines, not strikes in the vicinity of the lines as had been previously supposed. Working with his mentor in the company, A. C. Monteith, Harder made calculations on a design to make transmission lines safe from lightning strikes. Knowing how many direct strikes occurred on average on a mile of line per year, and knowing their average current, Harder calculated the grounding resistance of the towers so that the current would be carried through the ground wire and ground at the tower, without creating a high enough voltage to flash over the line.[13]

Because of his experience with these calculations, Harder helped to set the design specifications, such as the sizes of the resistors, for a special-purpose AC Calculating Board the company built in 1929.[14] Although it could solve only fixed-frequency problems, it superseded the numerical methods and desk calculators Westinghouse had previously used for these purposes.[15] These boards were built in quantity by Westinghouse and sold to electric utility customers all over the world. The AC Calculating Board continued in operation well into the 1960s, until it was finally replaced by digital computers.

In 1933 Westinghouse shut down the General Engineering Department as a Depression-era economy measure, and Harder transferred to the Switchgear Department, where he remained for five years (except for a six-month transfer in 1936 to the Relay Department in Newark). His main work during this time was to design the relay system for the electrification of the Pennsylvania Railroad.[16] He also worked on the designs of the switchboards for the Hoover Dam and of voltage regulators for the Safe Harbor Water Power Plant on the Susquehanna River.[17]

In 1938 Monteith, who had become Manager of Central Station Engineering, hired Harder as his engineering representative for the Middle Atlantic District, which included Washington, D.C. Harder remained in this position through the war. During the war, he worked with Captain Hyman Rickover to develop the power supply systems for the new naval vessels that were being built to replace nineteen American warships the Japanese destroyed at Pearl Harbor. These power systems did not drive the ships, but they provided all the on-board power. The challenge was to make power supplies that could swing heavy gun turrets and raise elevators, without dropping the voltage so much that it would disable the operation of the ship's radar and other sensitive electronic gear.

General Electric and Westinghouse collaborated on this project, each assembling its best engineers to work together on generators, exciters, turbines, governors, and voltage regulators. Harder handled the system work for Westinghouse, while Sil Crary did the same job for General Electric. For this purpose, Harder invented and built an electronic device, known as a regulating system simulator, to calculate voltage drop from sudden loads in systems that incorporated turbines, generators, governors, and voltage regulators. The simulator saved many hours of long-hand calculation, and Harder later used the simulator as a component in the Anacom.

Harder's war work was the basis for his doctoral dissertation, begun at the University of Pittsburgh in 1945. His dissertation gave a general solution to the voltage regulator problem.[18] Recognizing that there were just a few variables in a regulator system, Harder varied them all in turn and was able to determine from these trials the basic operating properties of a regulator system. His main result was that two-delay systems (e.g., ones involving an excitor and a generator) are always stable, whereas systems involving more delays are not necessarily stable, but may be made stable for a particular set of parameters through the use of feedback.

After World War II, Westinghouse had problems with many of its regulation systems for steel mills, paper mills, and generators, which cost the company millions of dollars. The company might get a steel mill in Gary running properly, but when the mill wanted to roll thicker or thinner steel, or to speed up or slow down the milling line, the process would frequently become unstable and the engineers at Westinghouse would be called back to restabilize the system for the new operating parameters. The Westinghouse engineers did not at first recognize any general principles in the problems they were experiencing, and they attempted all sorts of ad hoc solutions. Harder's dissertation provided a general answer to the problem, although even Harder did not fully understand the general situation until many years later. These mills were three- or four-delay systems, which could be stabilized for certain parameters, but which would become unstable when the parameters changed. Once magnetic amplifiers became readily available, Westinghouse used them to build what were essentially two-delay regulating systems for these mills, thereby providing stable operating environments despite variations in the operating parameters.[19]

Harder's career took a new direction in 1946, when one of Westinghouse's most impressive young engineers, G. D. McCann, decided to return to his alma mater, California Institute of Technology, as a faculty member in electrical engineering. Harder was selected to replace McCann as the company's consulting transmission engineer, director of lightning studies, and director of the recently conceived Anacom computer. In these positions, Harder gave many lectures and consulted widely on behalf of the company. He had considerable independence and worked on a number of interesting and challenging projects. One project was a study to measure the current in lightning strokes by placing recording equipment on top of the Cathedral of Learning at the University of Pittsburgh and on fire towers around Maryland, Pennsylvania, and West Virginia.[20] Among these duties, the most important turned out to be the one to build and then direct the use of the Anacom. At first, he had only one or two people working for him, but eventually his staff included 140 professionals in a unit that came to be known as the Advanced Systems Engineering and Analytic Department.[21]

Harder as Inventor

Especially during his first twenty years at Westinghouse, through the end of World War II, Harder was a fecund inventor. His Westinghouse career resulted in 123 patent applications and 66 patents. After the war, he assumed extensive managerial responsibilities, and his patent activity subsided. He regretted the lack of time for research.

As a young engineer, Harder was encouraged to return to Westinghouse at night and work on patentable ideas. He apparently did this with alacrity, happy to have the laboratory facilities entirely at his disposal. He felt an obligation to the company and to society to apply himself to invention:

> I had that [inventive] ability, and I wasn't making the most of it. I was turning in some patents, but in almost any field that I turned to I could see better ways of doing what they were doing. If I had that ability and I only worked eight hours a day at it and goofed off the rest of the time, I really wasn't making full use of my potential. It certainly made life interesting to have these problems coming up that seemed very difficult to solve and then come up with a unique solution to it that nobody else had thought about. It would occur to you, and that's a great feeling. That's almost like winning a football game.[22]

There was a pattern to Harder's inventive process, as he explained: "Many of my inventions were highly technical, or mathematical, in nature. The problem would be expressed mathematically, and I would try to find apparatus that would do what the resulting equations said had to be done. Some of my finest and most valuable inventions were a result of this process."[23] Harder was unusual in the power engineering field for the degree to which he relied on mathematics. His doctoral dissertation on voltage regulation was awarded by the Pitt mathematics department, not by electrical engineering. His last twenty years as a regular employee at Westinghouse were spent in the Analytical Department, where he mainly applied mathematical methods and computing machinery to problems of power engineering.

Harder's patents include several on analog computing, but most of them cover aspects of power engineering—mainly control of power systems, including numerous inventions of regulating and relay systems. Harder regards four inventions as his most important: the HCB relay, a high-speed distance-type carrier-pilot relay system, the economic dispatch computer, and a linear coupler. His other inventions, he argues, were incremental improvements to large fields.

The first of these inventions was the HCB (high-speed, current balance) relay, which was a new design for tripping the circuit breakers of a faulty transmission line.[24] The transmission lines of a power system generally form an interconnected network. When a fault occurs on any one of these lines, it must be disconnected from the system without disturbing the other lines in order for the power system to continue to function safely and properly. The highest speed protection is obtained through the use of a pilot circuit, essentially a telephone line over which a relay is run in order to compare the currents at the two ends of the line. If they are the same, then there is no fault on the line. If they are different, there must be a fault on that line section and it needs to be tripped out. For long transmission lines, instead of stringing long lengths of extra wires for the pilot circuit, a 60-cycle current is carried on the transmission line itself for this same function (known as carrier current pilot circuit). For short lines, pilot wires between the two ends are most economic, either carried in a control cable along the line or rented from the telephone company. The HCB is a type of pilot wire relay.

Ten kinds of faults can occur on a transmission line between the phase wires, a, b, and c, and the ground g: wire-to-wire (ab, bc, ca, abc), wire-to-ground (ag, bg, cg), multiple-wire-to-ground (abg, bcg, cag). It would be desirable to have a single voltage that could be compared over the pilot wires, regardless of which of the ten kinds of faults occurred; and this voltage must have a respectable value (i.e., one large enough to be read at both ends of the line), whichever kind of fault occurs. Through the method of symmetrical components, a mathematical technique well known to power engineers, Harder determined a network of resistors and reactors that would produce such a "discriminating" voltage when the a, b, and c currents were passed through it. This was the HCB relay. A simple operating element closes if the discriminating voltage differs at the two ends of the line and stays open otherwise. The network of resistors and reactors was inexpensive relative to the existing carrier relays, which comprised nine or more operating elements.

Harder invented the HCB relay in 1932, while he was in General Engineering, but it was not put into production at that time because of the Depression. In 1937, when it finally did become a company product, it was unknown to the Westinghouse relay department in Newark, which normally would have had responsibility for its development. About 1937, Public Service of Indiana was building a loop of short transmission lines around the city of Terre Haute, which were to be protected by pilot wire relays. General Electric offered their carrier current scheme, simply substituting a DC pilot wire signal for the carrier signal, thereby providing one-cycle (1/60 second) relaying. Customers were much more concerned about response time than they were about cost. They wanted to clear faults as quickly as possible in order to minimize damage and resume full operation, and Westinghouse had no comparable system with one-cycle response to offer in competition to GE's. Here is where the HCB story begins, as told by Harder.

The salesman from Indianapolis, Freddie Green, came into Switchgear one day, *and he was crying on my shoulder about Westinghouse having nothing to offer for this job and General Electric getting the order without any competition. And I said, "Well, I have this system that I patented four or five years ago. One weekend, a few months ago, when I was testing some of the carrier current relays on our miniature transmission line in East Pittsburgh, I took the weekend and went in and scrounged enough resistors and reactors to make up two of the required networks and tested it. It tripped for all the internal faults, and it didn't trip for any external faults." Now, I said, "It's completely undeveloped. If you want to take a chance on it, it's up to you." Well, he said, "What have we got to lose?" So we got Newark to put a price on it, and they priced it about half of what the General Electric one was. We still had a tremendous ratio of sales price to cost because the relay had only one little element that opened and closed. All the rest of the brain was in the network. These resistors and reactors, which were very inexpensive, had nothing critical at all about them. So it boiled down to a meeting with Joe Trainer, who was the chief engineer of the Public Service Company of Indiana, which ran the Terre Haute operation, and Arbuckle, the relay engineer, who had practically promised it to GE. He had done this since there was no competition. Now he had to go in to his boss and explain. He said, "Here Westinghouse is offering this relay that only has one contact. If that fails we don't have any protection." Joe Trainer looked him right in the eye and said, "All these years you've been wishing that instead of a whole mess of contacts you could have one contact that closed when it should and doesn't close when it shouldn't. And now that they're offering you exactly that, you don't want it. I don't understand." So the result was that GE didn't get to use their GMB [carrier current relay] even for the pilot-wire application.*

That HCB relay is still widely in use [several hundred are sold each year, sixty years after invention]. Patents only last 17 years so obviously anybody could build it, and [certainly] in the last few years [they have]. But there's a tendency for companies not to just pick up another company's product and start building it. So it's still largely a Westinghouse product. And it was worth many millions of dollars to the company in business.[25]

Harder's second major patent was for a high-speed, distance-type, carrier-pilot relay system. He developed this idea in 1936 during a 6-month assignment to the Westinghouse Relay Division in Newark, New Jersey.[26] During World War I, the Army Corps of Engineers began using carrier current (i.e., a few watts of 50 to 150 kHz current) to transmit messages over long power-transmission lines. After the war, power companies used this method for protective relaying circuits and communication over transmission lines. By 1930 both Westinghouse and General Electric were offering carrier current relaying. When a fault occurred, the fault detectors at each end of the line would start transmitting carrier. If the directional relay at terminal A pointed into the line, it would stop carrier transmission from that end. If the directional relay at terminal B also pointed into the line, then the fault must be on the line section between A and B. It would also stop carrier, and both ends would trip simultaneously, with no delay.[27]

The best previous relay scheme used distance-measuring relays, but involved sequential tripping for faults near either end of the line, a delay of about a half second for the second breaker. Until 1936 both General Electric and Westinghouse were using conventional three-phase directional elements, operating in three to five cycles. The circuit breakers then took about eight cycles to open. However, unbeknownst to Westinghouse, General Electric had spent a full year developing a very fast three-phase directional element and was now offering a one-cycle carrier scheme. It was almost impossible to sell a 3- to 5-cycle system in competition with a 1-cycle system. This jeopardized the business of not only the Relay Department in Newark but also the Switchboard Department in East Pittsburgh because about half of the relays were sold with switchboards. Many new transmission lines were being built at this time, and Westinghouse stood to lose many millions of dollars worth of relay and switchboard business. As Harder remembered the situation, "Not only were we a year behind, but how in the world were we going to develop a high-speed, three-phase directional relay without infringing on their [GE's] patents? We just had to have some interim scheme to offer in the meantime—no matter how crazy."[28]

Harder devised a scheme using the high-speed, single-phase directional elements of the Westinghouse distance relays, interconnected with many elements for detecting faults. On paper it would be one cycle. But eight separate relay elements, four directional and four fault detectors, all had to open or close correctly, coordinate with each other, and do it in less than 1/60th of a second. The probability of this seemed very remote to the Westinghouse engineers, but none of them had a better idea so they decided to test Harder's scheme. Within a few days, the laboratory engineer reported that the elements did seem to coordinate. After a much larger number of tests were conducted, not a single misoperation had occurred. The company immediately started to sell Harder's system. As Harder recalls:

> We really had the luck of the Irish. . . . It seemed that each job we sold, the customer would find some new advantage of this system that we had not yet thought of. We were just glad to have something that worked at all—in one cycle.
>
> One of the first customers observed that with a three-phase directional element, when you pull the test switch to test the relays, the transmission line has no protection. With the single-phase elements, there are four of them—three phases and ground. Any fault always involves at least two (phase-to-phase or phase-to-ground). Thus the test switch can be pulled on any one of the four to test it and still have 100% protection of the line. When all are in service, there is some redundancy.
>
> Another customer observed that if the carrier was out of service for any reason, the scheme reverted to distance relaying, the very best protection available before the days of carrier.

> Still another noted, "Well, I can buy distance relays today and add the carrier later when it is justified."
>
> And so it went. The 1938 paper[29] lists several other advantages of this new carrier-pilot relay system.
>
> The net result was that at the end of the first year we had sold 87 systems and lost only 13 sales. This continued for quite a few years. Westinghouse never did develop a high-speed, three-phase directional element. General Electric abandoned its system after a few years and brought out a system more like ours. Instead of losing millions of dollars worth of business, we gained substantially.[30]

In 1940 Harder made his third major patented invention, a linear coupler, which improved the detection of faults on power buses.[31] A typical high-volume bus on a power system might have several circuits connected to it, perhaps two or three transformers from local generators, and several transmission lines to various parts of the system. There might also be a "bus tie" to another high-voltage bus. Should a fault occur on the bus, it is necessary to trip all of the circuit breakers to it in order to avoid a fire. On the other hand, for a fault on a line just off the bus, you need to trip that line without tripping all the other lines connected to the bus so as to disconnect as little of the system as possible. Theoretically, the sum (totalization) of all currents into the bus will be zero, unless the fault is actually on the bus. Current transformers are typically used in all the circuit breakers to reduce the high primary currents to small secondary currents for this totalizing.

If the bus is at or near a generating station, the short-circuit current contains a large DC transient, which saturates the iron of the various current transformers unequally. The totalized secondary current may be high enough to trip, even if the fault is not on the bus. Many schemes have been devised to avoid this spurious tripping, with varying degrees of success.

Harder's linear coupler omitted the iron and hence avoided the saturation problem.[32] The invention was based on the fact that if the device is a perfect toroid, it is astatic and the totalizing is perfect as long as each circuit goes somewhere through the hole of its toroid. This was the best bus-fault protection available for many years, and even today, half a century later, many of these devices are still in use.

Harder's last major patent, made in 1953, was for an economic dispatch computer.[33] The computer simulated a power generating network comprising generators, transmission network, and loads, in order to optimize the generation of power in interconnected systems, or in the parlance of the electric utility industry, to give it "economic dispatch."

Power companies knew the generating cost for any individual generating unit once the cost of fuel and the efficiency of the unit was known. However, a loss occurred when the power was sent over the transmission lines. If there were only one generating unit, it would not be difficult to determine this loss. A typical network, however, contained perhaps fifteen power stations, each of which affected all the others. To calculate the economic dispatch for a given power station, that is, the amount of power the station should dispatch for the lowest overall cost of the power system, thus required solving fifteen simultaneous equations. This made it difficult to determine the economic dispatch for the system.

Harder convinced one of Westinghouse's customers, Allegheny Power, to have Westinghouse build for them an economic dispatch computer. It was of analog design, with cost curves for individual generating plants represented by resistors, together with summing amplifiers and servomechanisms to solve the simultaneous equations that must be solved to obtain the economic dispatch when considering system losses.[34] The overall transmission loss formula of the system was represented in the computer. The operator could set the generating capacity in megawatts desired from the power network, and the computer would calculate the needed amount of power from each station on the network in order to achieve economic dispatch. (See Figure 2.)

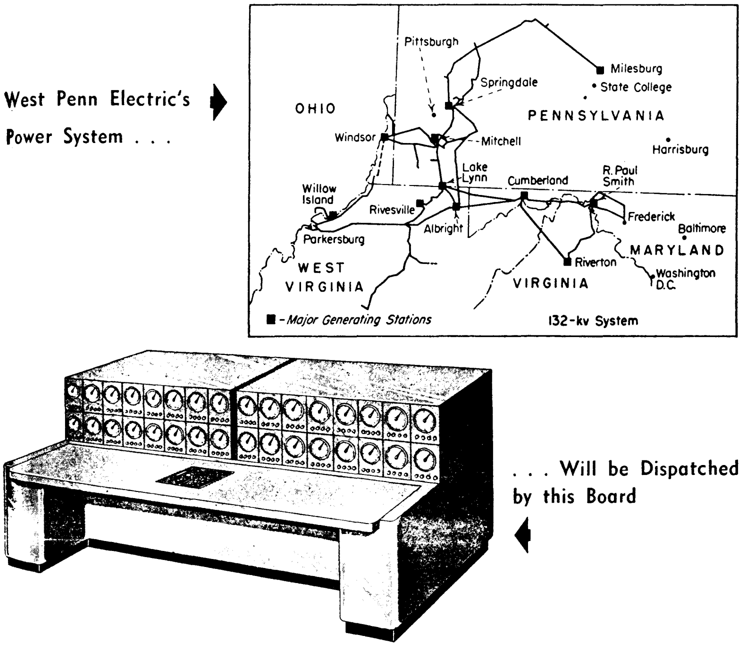

Figure 2. Harder's economic dispatch computer.

The economic dispatch computer is the one example of an invention in Harder's career upon which he looks back feeling that an important opportunity was missed:

> This economic dispatch computer should have been commercialized. No question in my mind that that was a bad mistake. Part of the responsibility is mine. I was young and immature. I should have gone to bat for it, but it never occurred to me that this was an excellent product that should be used. I just did my job getting that [first] one designed, built and installed and then forgot about it. I had other things to do—I was busy. But looking back at it—that was a bad mistake.[35]

Harder's staff built and adjusted the economic dispatch computer and knew how it operated, but the Switchgear Department was responsible for selling. Presumably as a result, no other economic dispatch computers were sold—even though Harder believes that Westinghouse would have been able to sell thirty or forty of them in the national market.

Specialized Calculating Devices at Westinghouse

Harder's greatest accomplishment, the Anacom, was the result of a plan by Westinghouse just after World War II to replace many of the specialized computing devices it had built over the previous quarter century with one, more powerful, general-purpose calculating machine. Before turning to the design, development, and application of the Anacom, we review these early computing devices.

Analog computing instruments and machines were popular among engineers in the early twentieth century for at least four reasons: they were effective at solving problems of interest to engineers; they operated according to principles that engineers readily understood (given that the analog machines were often scaled-down models of the problems under investigation); they did not require engineers to learn abstruse numerical methods, as digital computing devices did; and they could often be built in the engineering laboratory, much like specialized test equipment.

The demand for analog computing devices, especially complex ones, increased through the mathematization of engineering. The expansion of electric power after World War I and a consolidation and increase in the scale and scope of power networks led electrical engineers in particular to develop new analog computing devices. The product integraph and differential analyzers of Vannevar Bush, the network analyzer of Harold Hazen, the simultaneous linear equation solver of J. B. Wilbur, and other analog computing devices constructed at MIT in the interwar years are well known.[36] General Electric, which needed such devices for its work, worked closely with MIT on some of these machines and used them after they were completed.

Westinghouse took a different course from General Electric by building its own machines. The first of these machines was a DC Calculating Board, built by the company after World War I.[37] It was used to calculate short-circuit currents in power systems as part of the process of applying circuit breakers and relays. These calculations became complicated when several power stations were connected to a system, which occurred with increasing frequency after World War I.

Westinghouse engineers determined that a model network containing only resistance could give approximate results to networks also involving reactance and impedance, thus reducing the complexity and cost of the network. The DC network model, known as the DC Calculating Board, which Westinghouse engineers built, consisted of thirty adjustable resistors mounted in three frames, able to take on eleven different resistances between 50 and 1000 ohms. (See Figure 3.) Buses connected the units and subunits. Power was supplied from a 500-watt motor generator able to deliver 50, 100, or 120 volts at up to five amperes. Results were read off an ammeter, which could be connected flexibly to any resistor, and a voltmeter, which could be connected to any point of the network.

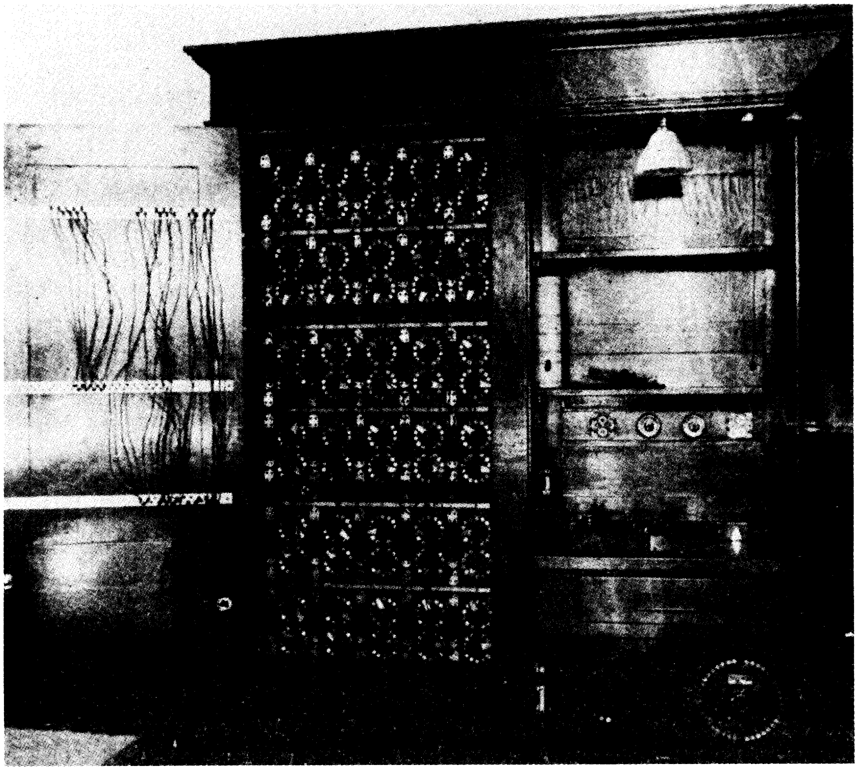

Figure 3. The DC Calculating Board.

Some problems could not be solved on the DC Calculating Board, such as load flow calculations, which involved phase angles and complex impedances.[38] Numerical methods and desk calculators were used instead in these cases.[39] Harder and fellow engineer Frank Green were among the last people to calculate an extensive power system using desk calculators when, in 1928 or 1929, they completed a calculation of the Pennsylvania Railroad transmission/trolley (132 kV/12 kV) system, including the Philadelphia suburban electrification network and the main line extending as far as Trenton, New Jersey.[40] The two engineers worked two weeks at desk calculators to make and check their calculations. The product of these calculations was a table of self- and mutual-impedances to all the load points on this large network.

Desk calculators were replaced around 1930 by an AC network calculator (see Figure 4), and numerical methods were not used in making power calculations again until the mid 1950s, when digital computers such as the IBM 650 and 704 became available.[40] Even after digital computers began to be used for power applications, the AC Calculating Board continued in use for many years because it was easier to set up these power problems on it and because it provided excellent visualization of power system phenomena.[41]

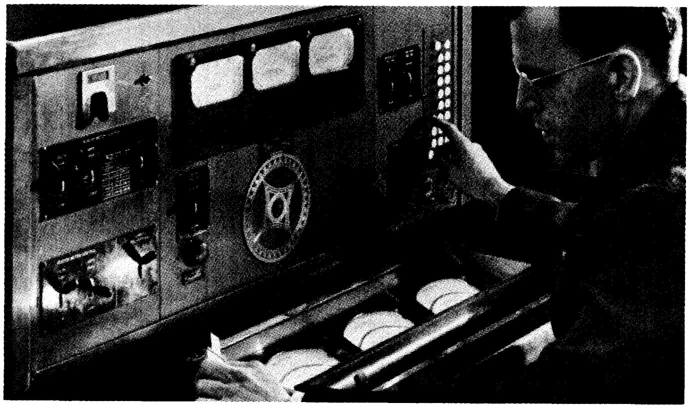

Figure 4. One side of the AC Calculating Board.

The AC Calculating Board had two major advantages over previous calculating equipment used in the electric power industry. One was its ability, unlike the DC Calculating Board, to account for phase-angle differences of voltage in different parts of a network. The other was the incorporation of a whole range of features that made for easy and flexible use: capability to represent a wide range of electrical constants, flexibility in connecting and adjusting circuits, straightforward checking of problem set-up, and simplicity in metering answers.

The AC Calculating Board was used for four general kinds of problems: (1) those associated with operating issues, such as voltage regulation and current and load distribution, of complex transmission and distribution systems involving as many as 36 generating stations; (2) the study of system stability under both steady-state and transient conditions; (3) the investigation of mutual induction between parallel conductors, as in AC railroad electrification; and (4) in short-circuit analysis of interconnected power systems with large power concentrations—for which high accuracy was desirable.

The AC Calculating Board was arranged in a U-shape, each side approximately twenty feet long. The originators, H. A. Travers and W. W. Parker, explained the layout:

> The board consists of fifteen cabinets of standard steel office desk construction, in which are located the various units of resistance, reactance, capacitance, power sources for simulating synchronous apparatus, cord-and-jack assemblies to permit reproducing any miniature system network to be studied, and suitable current and voltage receptacles whereby the metering equipment may be inserted in any component of the miniature network. In the middle is located a desk containing the metering equipment [for reading phase-angle, voltage, current, and power], as well as ordinary office desks for the use of the operators. A synchronous motor-driven generator set supplied three-phase, 220-volt, 440-cycle power. Each source of power, representing a generator station, consists of a three-phase, 220-volt, 100% induction regulator and a phase shifter.[42]

An analysis was carried out by writing an electrical network diagram, scaling the model through the use of an impedance conversion factor, setting up circuits to model the network on the calculating board, adjusting the generating sources, and measuring the results with meters. Individual components were accurate to within 1.5 percent, many errors were compensating, and system solutions were generally within 15 percent accuracy and sometimes much better.

The next Westinghouse special-purpose calculating device was the Electrical Transients Analyzer, built in 1936 according to the design of R. D. Evans and A. C. Monteith.[43] It was used in investigations of various kinds of electrical transients. It included elements of the AC Calculating Board and an 8-stage rotating synchronous switch, which repeated the transient and enabled it to be displayed and measured on a cathode-ray oscillograph. The timing of the opening and closing of the several switch contacts could be controlled, enabling the engineers to investigate complex switching and arcing ground transients. While the AC and DC calculating boards were primarily used for solving short-circuit, steady-state, and stability problems of electric power systems, the Electrical Transients Analyzer and all subsequent special-purpose analog calculating devices built by Westinghouse prior to the Anacom were intended primarily for use on transient problems.

During the war, Harder built a Servo-Analyzer (also known as the

Regulating System Simulator) as part of his work on the power supply systems for the new ships for the US Navy to replace those destroyed at Pearl Harbor. The system enabled him to optimize the voltage regulating systems for these power supply systems. In many respects, the Servo-Analyzer was similar to the Electrical Transients Analyzer. It had a commutator for repeatedly inducing transient voltage or current into the model network and used oscillographs to measure transients. The major addition to this calculating equipment was an electrical analog for a regulating system, consisting of delay circuits (of variable resistance and capacitance), damping transformers, and electronic amplifiers.

In 1945 G. D. McCann, H. E. Criner, and C. E. Warren devised a Mechanical Transients Analyzer. (See Figure 5.)[44] This equipment incorporated the Electrical Transients Analyzer in a system to calculate transient mechanical problems, such as transient torques in the shafts and couplings of turbo-generators during short-circuits. The Electrical Transients Analyzer was coupled with an electrical analog of the mechanical system, in which force, displacement, and velocity in the mechanical system were represented by transient voltages or currents in the electrical analog. Many problems were adaptable to this machine, including mechanical stresses from "plugging" steel mill drives, peak stresses in air frames at the onset of flutter, transient coupling stresses in long railway trains, and transient loading of cranes and hoists. (See Figure 6 for an example.)

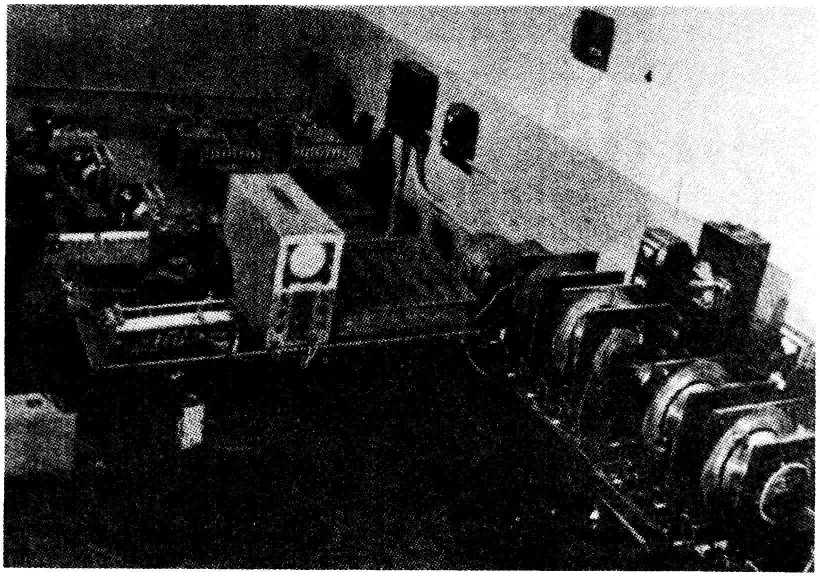

Figure 5. The Mechanical Transients Analyzer.

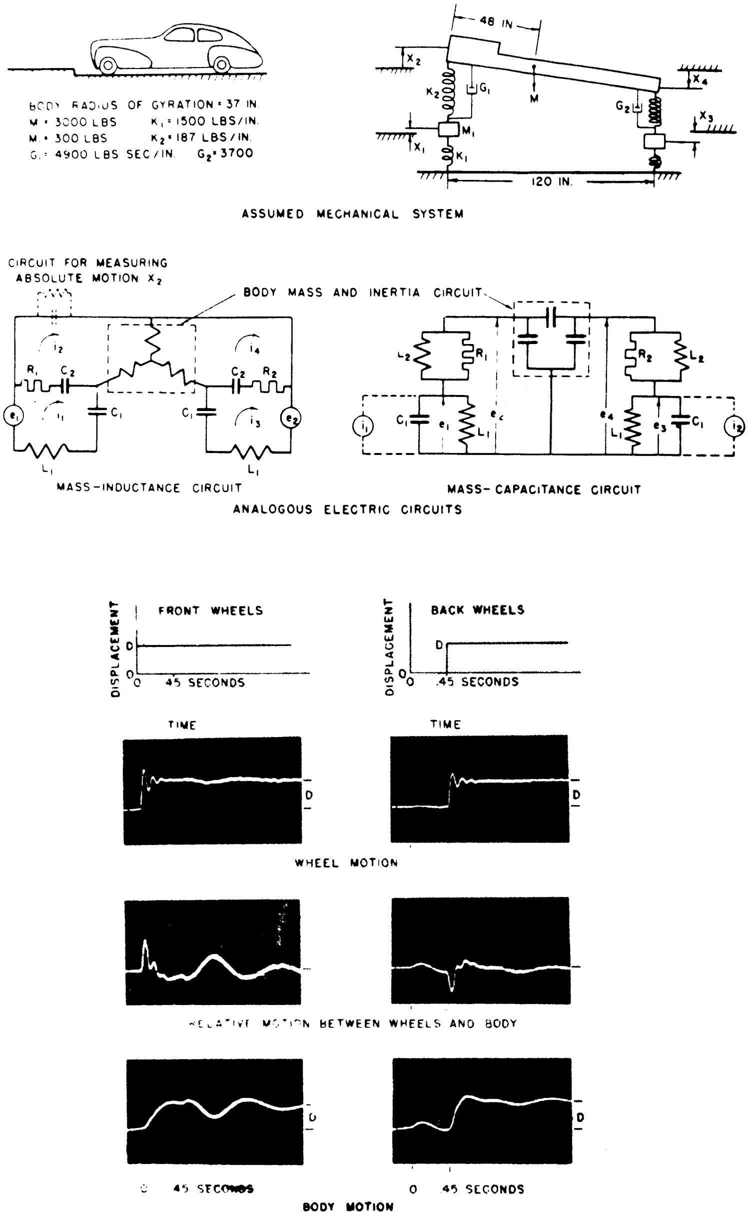

Figure 6. An illustration of the use of the Mechanical Transients Analyzer for studying the ridability of a vehicle. Part (a) shows the assumed mechanical system and the analogous electrical circuits, Part (b) the motion of various parts of the vehicle.

The Anacom

In the 1930s and throughout the war years, electric analog computers were effectively employed in the study of applied mechanics, hydraulics, heat flow, transients in electrical circuits and machinery, and electromechanical systems such as servomechanisms and control.[45] Soon after the war, in 1945, Gordon McCann, a Westinghouse transmission engineer who had made a name for himself within the company for his investigations of lightning, made a survey of all the possible uses of electric analog computers, paying special attention to their potential use in the design and application of electrical equipment. He became involved in this work through his association with R. D. Evans, the codesigner of the electrical transients analyzer, who worked in the same section with him, and through his collaboration with the mechanical engineer H. E. Criner on the mechanical transients analyzer. McCann also made a study of other calculating technologies to determine their suitability to the studies of electrical equipment that were of greatest interest to Westinghouse. McCann deter-mined that a general-purpose electrical analog computer more powerful than any of Westinghouse's existing special-purpose analog calculating devices would be the "best adapted generically and economically to the scope of problems under consideration."[46]

McCann began to design a new general-purpose computer, and proceeded as far as building a small prototype of the Anacom (short for ANAlog COMputer) with his own hands, using the rotating synchronous switch, many resistor and reactor circuits from the AC calculating board, and the servo-analyzer. Harder, who used the prototype for his dissertation research (see Figure 7), was well prepared to replace McCann in the design of the full-scale Anacom, when McCann left for Cal Tech and Harder assumed all of McCann's responsibilities. It was soon arranged for Westinghouse and Cal Tech to cooperate in the construction of similar, general-purpose analog computers at each institution.[47]

Westinghouse allocated $300,000 for the design and construction of the full-scale Anacom. Although it would have been possible simply to cable together a number of pieces of equipment, Harder decided that there was value in building the Anacom to look like a real machine. He used first-class components and had high-quality cabinets specially built to house the various units. He is convinced that this was an important reason why the machine survived for over forty years. The quality construction, together with the unknowns of building such a novel device, however, caused the design and construction costs to mount to $500,000—an overrun which at first upset Westinghouse management, but which was eventually forgiven when the machine began to pay dividends. Part of the expense was in the materials that needed to be used in the full-scale machine. In scaling up, there were serious questions about how to build a large machine without increasing the capacitance of the wiring to a point where it vitiated the results. Special low-loss reactors and transformers composed of unusually large amounts of expensive molypermalloy iron were used to avoid this problem.

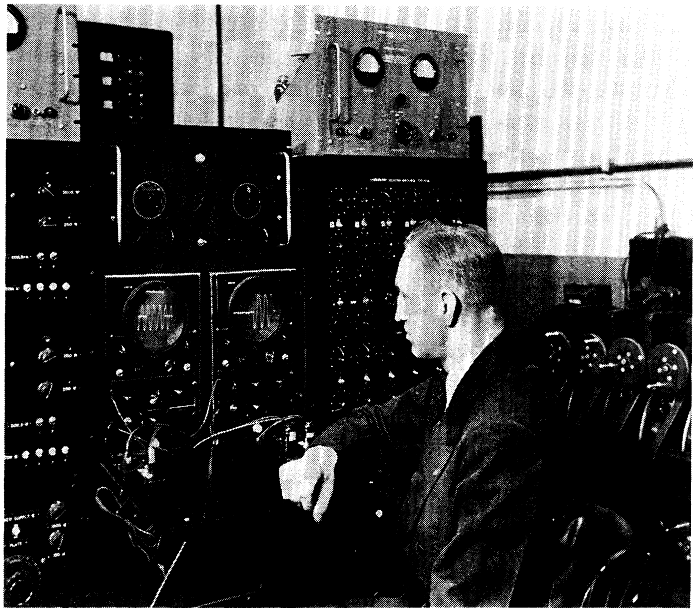

Figure 7. Harder at the small prototype of the Anacom.

Like other analog computers, Anacom had equipment serving three purposes: (1) "forcing functions" to generate electrical voltages representing the forces applied to the physical system under investigation, (2) an analog of the system being studied (i.e., an electrical system governed by the same differential equations that govern the system under investigation), and (3) equipment to measure the changes that occurred when the forcing functions were applied to the analogous circuit. Forcing functions were achieved with 60 hertz and 400 hertz power supplies, an audio oscillator, and a synchronous switch. The analog was built from resistors, low-loss capacitors, hi-Q inductors, and transformers—together with amplifiers when servomechanisms were being modeled. Measuring equipment included ammeters, voltmeters, wattmeters, harmonic analyzers, and cathode ray oscillographs whose readings were recorded photographically.

The choice and arrangement of the units comprising the Anacom were determined by the kinds of problems that were likely to be calculated most frequently.[48] The Anacom occupied a room forty feet long. Along one wall were the circuit element cabinets and the plugboards for connecting them. These were used to form the electrical networks representing the problem analog and the forcing functions. The electronic power supply cabinet occupied the middle of this wall. The 440-cycle power supply could be placed almost anywhere since cable length was not a concern, so it was situated on the opposite wall. Amplifier and multiplication cabinets were placed on an end wall near the metering desk. Some of these amplifier cabinets held time-delay elements. The AC Calculating Board, which was used for steady-state problems rather than the transient problems primarily done on the Anacom, was situated in an adjacent room, to facilitate interchange of information between them. Figure 8 shows scenes from the construction of the Anacom.

Improvements were made to the Anacom over the years.[49] For example, switches were changed several times. The first switches were noisy, motor-driven mechanical devices, which were replaced in 1953 by switches using vacuum tubes. Around 1970, changes were made to increase capacity and speed up the set-up time by building in prewired transmission line sections with three-phase plugging to replace old spring-retractable cables that were copies of the AC network calculator plugs used in the 1940s and early 1950s. The old cables were used to build "pi sections" to ease the setup of transient problems. At the same time a better arrestor model was built in, using advanced electronics. With these changes, the machine was renamed Anacom II.

The next major change, to Anacom III, occurred in 1980. (See Figure 9.) As the general manager responsible for Anacom at the time recalls the change:

> The change to Anacom III was around 1980. By then statistical/probability measures had been introduced into the art of insulation coordination, and it was necessary to make many runs with random breaker operating times to get the probability distributions of the overvoltages. This was manpower intensive and therefore expensive. [The fastest way to do the calculation was by having] Anacom run by a digital control computer which could work through the night unattended. So we added an HP [Hewlett-Packard mini-] computer to control the switches and to gather the data. Cameras were eliminated, and the computer was programmed to plot the results, even the probability distributions, report-ready. That was Anacom III.[50]

The Anacom was designed to be a general-purpose calculating device, but with a configuration that enhanced its utility in applications of interest to Westinghouse. It was originally conceived mainly to do calculations associated with transient analysis for the electric utilities, electrical transients that arise in the design of generators and motors, applied mechanics problems such as vibration analysis, and problems associated with the statics and dynamics of beams. Over time, the number of applications grew, expanding beyond these original categories to a wide array of applications. The accuracy of one percent to five percent was satisfactory for most applications.

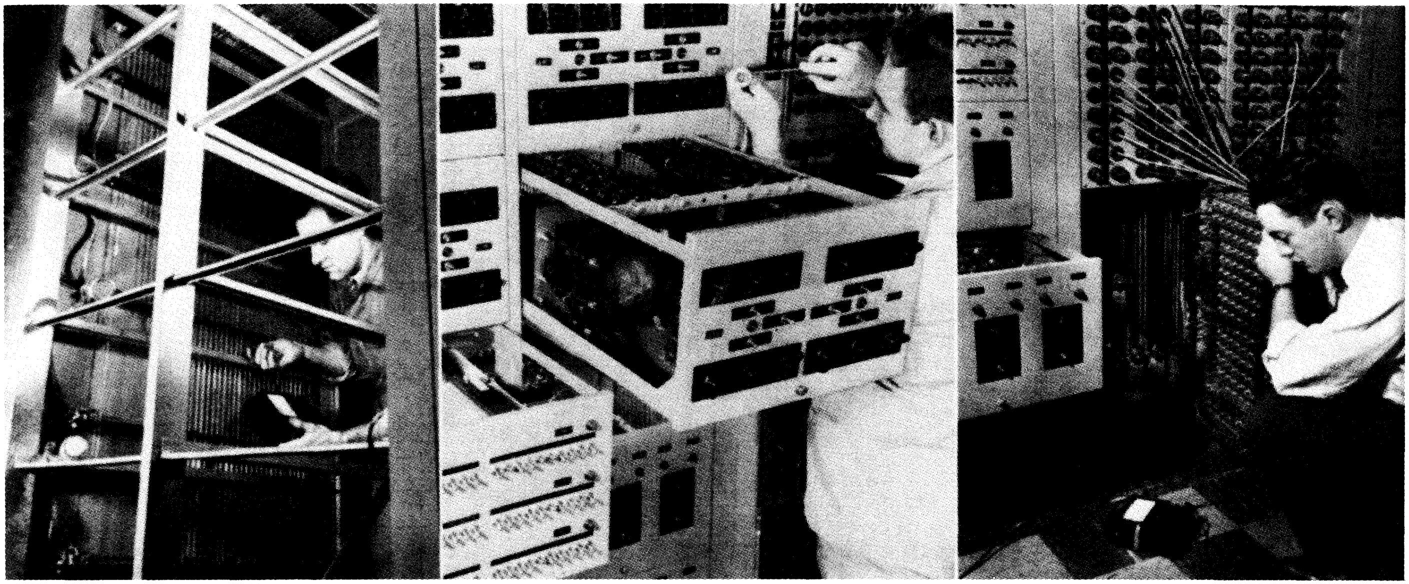

Figure 8. The Anacom under construction.

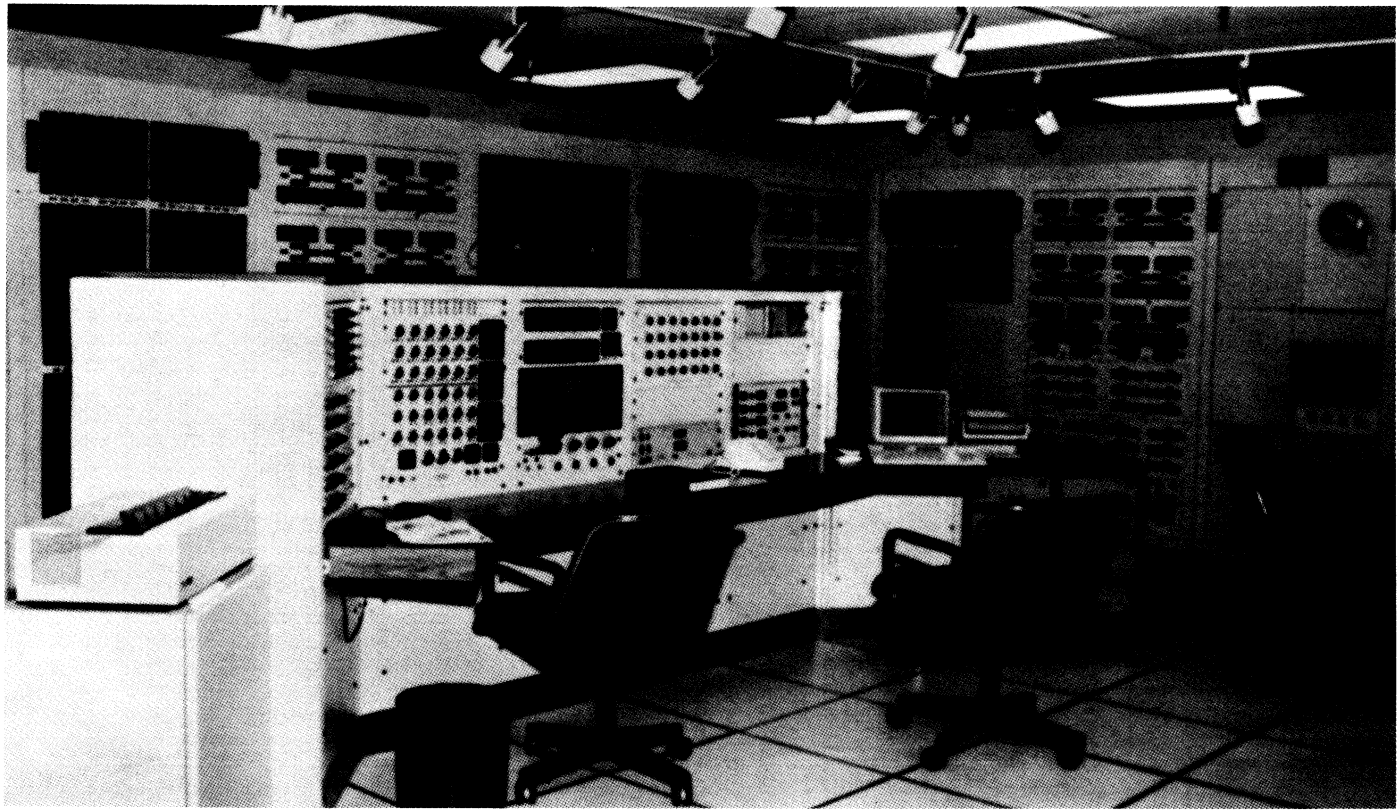

Figure 9. The Anacom III.

> *In the direct-analog method all elements of the physical system, or nearly all, have their counterparts in the analog and as such are under the direct and independent control of the operator. To study the effect of varying a certain element of the system, the operator need only vary the corresponding element of the analog. In rare cases this may involve a lessened mathematical generality and the use of a few more elements. Some of the advantages of a direct 1-to-1 correspondence between analog elements and system elements in design work are quite apparent. However, not until one enters the nonlinear domain of saturation, of fluid flow, of discontinuous functions, of hysteresis, and of limiting action does the great advantage become truly evident. Rapid and accurate solutions of complex nonlinear problems can be obtained readily.*[51]

The Anacom quickly became the most important computational tool of Westinghouse and was used by almost every manufacturing division. During the first sixteen months of operation, 141 problems of 43 distinct types were solved using it.[52]

The Analytical Department did a wide range of calculations soon after Anacom became available in 1948. Using Anacom and other calculating machines, the Analytical Department did calculations for the design of the blades for steam turbines, the study of transient torques in the shafts and couplings of machines, lightning and switching transients in power systems, and the regulating systems (mentioned above in the discussion of Harder's dissertation) for steel mills, paper mills, and voltage regulators. Anacom was used both for internal product development and for contract work for outside organizations.[53] Anacom was also used in consulting projects for regional utility companies, such as the design of Virginia Electric Power Company's first 500-kV system, which was one of the first networks for which it was determined that switching transients were an important system design parameter.

One calculation done in 1948 deserves particular mention: the design of the large compressor blades for the Tullahoma Wind Tunnel in Tennessee. The problem involved the determination of the blade's higher modes of vibration. Because the design problem required knowing third and fourth modes of vibration, and it had only been possible to calculate the first two modes of vibration, designers had previously resorted to building and testing successively larger models—an expensive and labor-intensive process. R. H. MacNeal, working with the Cal Tech analog computer, developed an analog of a cantilevered beam, and Harder's group set this problem up on the Anacom. Because the differential equation representing the cantilevered beam had a closed-form solution, this problem provided a test of Anacom's accuracy. When the test was satisfactory, Harder's group modified MacNeil's analog, tapering the beam and twisting it into the shape of a turbine blade. Although there was no closed-form solution for the equation representing the blade, Harder assumed the validity of the analog and used Anacom to make the Tullahoma design calculations. Once the analog was set up, it was easy to apply an audio oscillator to it and measure modes of vibration and natural frequencies. In 1949, when Westinghouse acquired an IBM 602A for its accounting department, Harder's group redid the calculations numerically and showed Anacom's accuracy on this calculation to have been within two percent.[54]

The importance of calculation to Westinghouse increased after the war, and Anacom was supplemented by digital computers. The company acquired an IBM Card-Programmed Calculator (CPC) in 1952 and an IBM 650 in 1954. In the 1950s the company also added a PACE electronic differential analyzer (a small, relatively inexpensive machine manufactured by Electronics Associates, Inc., which was based on the design of the wartime Bell Labs Mark-9 gunnery computer used to shoot down buzz bombs). Thus by 1955 Harder's Analytical Department contained the DC Calculating Board, the AC Network Analyzer, the Anacom, the PACE electronic differential analyzer, the IBM CPC, and the IBM 650. The company later added additional digital computers: an IBM 704 in 1956, and later an IBM 7090, an IBM 7094, and several Cray supercomputers.[55]

The digital computers first supplemented and later supplanted the analog devices for many problems. The analog machines were faster than the CPC, but the latter received increasing use because its card-programming feature allowed programs to be as long as one liked and to be run by a technician-operator rather than a skilled engineer. The IBM 650, with its magnetic drum memory, was powerful enough that it began to be used for power network problems that for twenty-five years had been handled on the AC Network Calculator. Regulating system problems, which were originally solved on the Anacom, were moved to the PACE machine. After 1970, when the electronic differential analyzer was simulated by the MIDAS (Modified Integration Digital-Analog Simulation) program, most regulation problems were carried out on digital computers simulating electronic differential analyzers. The DC Calculating Board was then no longer used for power system problems, but was applied in the 1950s to diffusion and heat flow problems that could be represented in the form of the Laplace or Poisson equations. The DC Board was particularly useful in the design of early nuclear reactors, to calculate the diffusion of fast flux and slow flux fields.

Anacom survived in the digital computer era.[56] One of its great virtues was that, once an analog was set up, everything could be measured immediately. It was used in the 1950s, for example, for oil flow problems, bearing lubrication problems, diffusion problems, nuclear reactor design, and many other kinds of problems represented by differential equations. As digital computers improved rapidly during the 1950s, progressively more problems were shifted from the Anacom to digital machines. Anacom was sometimes used in tandem with a digital computer; for example, a network solution would be done on the Anacom and the corresponding stability study on the digital computer. After 1970, digital computers were used for all problems except transient, lightning, and oscillatory problems and nonlinear problems of electric power systems. By the 1980s, most lightning problems were also solved digitally. Advertising literature for the Anacom indicated that, in 1990, the machine was still being used for the study of electrical transient phenomena and for the analysis of industrial power systems, such as "power networks that supply arc furnaces where switching transients and resonances are of primary concern."[57]

The Anacom had its greatest value to Westinghouse and its customers, who benefited from the increased efficiency of design and the enhanced productivity it provided. Anacom was also the model for a number of other analog computers. Westinghouse built a copy for J. F. Calvert's laboratory at Northwestern University, which used it mainly for armament studies under contract to US Army Ordnance.[58] Several machines similar to the Cal Tech analog computer were built by McCann's company, Computer Engineering Associates, for the aircraft industry.[59] Similarly designed machines were built by CEZI (the Edison group in Italy) and ERA (a British engineering firm). Altogether, there were probably twenty or thirty Anacom-like machines around the world.

Professional Activities

Harder extended his influence beyond Westinghouse through his involvement in the professional community. His knowledge of analog computing led to his appointment to the American Institute of Electrical Engineers (AIEE) Computer Committee, on which he served throughout the 1950s and early 1960s, and whose subcommittee on analog computers he chaired. In the early 1960s he served as the chairman of the AIEE Science and Electronics Division. When the AIEE and the Institute of Radio Engineers (IRE) merged to form the Institute of Electrical and Electronics Engineers (IEEE) in 1963, Harder was primarily responsible for undertaking the merger between the AIEE Computer Committee and the IRE Professional Group on Computers—a tricky assignment because the two organizations had different philosophies for handling their computer special-interest groups. AIEE elected a small group of twenty people to organize its activities, while IRE allowed any of its members who had an interest in computers—thousands of engineers—to join its special interest group. Harder became a Fellow of AIEE in 1948 and served on the AIEE Board of Directors from 1960 to 1962. He was a member of the IEEE Board of Directors from 1966 to 1968.

ASPRAY: *If you were to point to some things that had industry-wide or profession-wide value, what specific things that you contributed would you point to?*

HARDER: *Well, I think the professional society activities would fit best in*

> *that category: The contributions to IEEE, IFIP, and AFIPS all were certainly industry-wide things. It's a way that we have of unconsciously sharing large developments. In the IEEE all of the current contributions end up in papers and are presented for everybody to know about. They are the inspiration and starting point for the next group of papers. So in a sense we are carrying out this development of electric power systems, or whatever you're working on, jointly. All the engineers are working jointly and contributing their efforts to this pool. We're pooling it, teaching each other and advancing much faster than if we ever tried to keep that all secret to ourselves. So it's this cooperative development through joint sharing of things in the industry-wide IEEE and similar organizations that is responsible for the huge development of electrical engineering and computers and electronics and all that in this country. If we didn't have that, it would never have developed as fast as it has. So I think that my part in the IEEE, IFIP, and AFIPS contributed to this overall advance more than my specific contributions in just what I did in Westinghouse.*[60]

Harder was also active in the International Federation of Information Processing (IFIP), the international computer organization that arranged for multinational glossaries of computer terms, did basic standards work on ALGOL and other programming languages, formed study groups on administrative data processing and computers in medicine, and much more. Harder himself was responsible for IFIP forming in 1969 its Committee on Computer Applications in Technology, which studied the "research, design, manufacture, operation, and control of products and physical systems, as well as the related programming methods."[61] He believed in the importance of IFIP's work:

> One of the greatest ways for advancing our profession, and the industry in which we all contribute and make our livelihood, is the professional technical interchange provided by our technical societies. Here each advance is brought to the attention of our peers, is discussed, criticized, added to, and soon inspires the next advance. Here we meet new friends, though possible competitors in industry, and share in the advance of our profession.
>
> In the various countries of this world this interchange is provided by member societies, the member dues largely financing the operation. However, in the international federations of societies, such as IFIP, ways have also been found to finance an international professional interchange, for the benefit of the whole world. The secret lies partly in the fact that a tremendous international interchange can be effectively organized and carried out at a tiny fraction of the total cost of travel, time, and services provided by all the participants. That small cost can be provided for by very carefully managed budgets, with the limited income from national dues, congress and conference surpluses, and royalties from publication.[62]

Harder orchestrated this financial plan while he served as the chairman of the IFIP Finance Committee from 1966 to 1969 and as IFIP Treasurer from 1969 to 1972. He also served as US Representative to the IFIP General Assembly and made all the US arrangements for the first IFIP Congress, held in Munich in 1962.[63]

Harder's early involvement with IFIP led him to be serve as president from 1964 to 1966 of the professional society that represented the United States in IFIP, the American Federation of Information Processing Societies (AFIPS). AFIPS had only three original members, AIEE, IRE, and the Association of Computing Machinery (ACM). During his presidency, Harder began the sensitive business of expanding the membership, screening out inappropriate organizations, accepting as members the Linguistic Society and the Society for Computer Simulations, and beginning the process of reallocating the revenue of the Joint Computer Conferences to the member societies. He also oversaw the Joint Computer Conferences at a time when the computer industries on both sides of the Atlantic and the Joint Computer Conference exhibits were expanding rapidly.

As a result of his technical and professional achievements, Harder was the recipient of several awards. In 1962 he received the AIEE's Lamme Medal "for meritorious achievement in the development of electrical machinery." In 1971 he received the AFIPS Distinguished Service Award "in recognition of his outstanding contributions to the federation, his guidance and leadership as AFIPS President, and his many contributions to the international growth of the computing profession." He was awarded the Westinghouse Order of Merit, the company's highest recognition. In 1990 he received the first and only Lifetime Innovation Award given by Westinghouse, which cited "his 66 issued patents and his technical achievements as instrumental in increasing the corporation's stature in engineering and innovation" and his work as "a strong force in the development of young engineers as designers of electrical apparatus."[64] He was elected to the National Academy of Engineering in 1976. He has also been a member of CIGRE (*Congress Internationale pour le Grande Reseau Electrique*, an international organization dealing with large electrical systems), the Association for Computing Machinery, the American Mathematical Society, and the National Society for Professional Engineers.

Consultant and Author

In 1965, at age 60, Harder decided to retire from Westinghouse. The Analytical Department was running smoothly and he had been doing the job for twenty years, so he thought it was time for a change. Retiring was not as easy as he had anticipated. Almost immediately upon giving word of his retirement, Monteith called him downtown to corporate headquarters and persuaded him to continue at Westinghouse as a senior consultant.

The company had a broad licensing agreement with Siemens, but Monteith worried that Westinghouse was not gaining all that it could from this agreement. Over the next five years, Harder made fifteen trips to Germany to visit the Siemens laboratories and talk with their engineers. He uncovered in Germany many technical ideas of value to Westinghouse, and he was able to stimulate a number of Westinghouse engineers to visit Siemens and exchange technical information.

> *I would uncover things that were of interest. I remember in the nuclear field, I found out that Siemens had a way of putting boron into and out of the water by an equilibrium process. At one temperature and pressure it would dissolve in the water, and at another temperature and pressure would go out of the water. I got a consulting engineer from the Nuclear Department to go along with me. He was taking notes galore. It turned out that the boron in the water is a shim. You have rods that control the reactor, but to get the starting point, the boron is a shim to where you want to be operating. Siemens's reactors were all baseload. They had no need to change. But they were developing this in the laboratory. They understood it and were developing it. Apparently our fellows had never heard about it. So I took him over, and we put it right into use in our reactor, and it saved two or three hundred thousand dollars over a job. To get the density of boron down, we didn't have any way of taking it out of the water and putting it back in. So that was probably the most spectacular of the things I learned.*[65]

At the end of five years, Westinghouse was forced by legal considerations to sever its long-standing licensing agreement with Siemens. General Electric had a broad licensing agreement with Germany's other large electrical manufacturer, AEG. When Siemens and AEG formed joint venture companies to manufacture large electrical equipment, Westinghouse felt obliged to sever the relationship with Siemens because the US government was already scrutinizing Westinghouse and GE for antitrust activity, and this back-door connection through Germany increased the appearance of antitrust activity between them.

Harder was ready in any event for "retirement" so that he would have time for his own research and writing interests. Many of the 150 papers Harder published during his career presented broad overviews of technical areas.[66] He chose a similar objective for his principal retirement writing project: a book intended to give an overview of the nine sources of energy in the world (coal, oil, gas, nuclear, hydro, wind, solar, geothermal, and biomass).[67] During the several years he devoted to research on this book, he visited energy installations across the United States and western Europe. The book described the characteristics of each of these nine sources of energy, plus the overall resources, physics, chemistry, transportation, and storage of energy. He considered such issues as world population and world food consumption as energy issues.

Conclusions

Many historians believe that the most challenging and interesting intellectual work occurs during the formative years of an engineering discipline. For this reason, historians of power engineering have mainly concentrated on the period up to the 1920s, by which time the fundamental elements of power systems had been determined and power grids had been laid in most urban areas.[68] Harder's career shows, however, that many challenging and interesting problems remained in the 1930s, 1940s, and 1950s—especially in the regulation and control of power systems. Some of these problems involved the need for additional control as power grids were interconnected and increased in scale; others concerned the regulation of new power machinery (generators and motors) and systems incorporating them (steel mills, paper mills, and so on).

Harder's mathematical ability, and his deft application of this talent, set him apart from many of his power engineering colleagues. Mathematical analysis was fundamental to his inventive process as well as to his later work managing the Analytical Department. While a cursory examination of his career might uncover little connection between these two stages of his career, a closer examination shows a strong thread of continuity involved increasingly with mathematical modeling and computational tools.

Harder did not set out consciously on a career in computing. His strong college training in mathematics was simply part of the standard electrical engineering curriculum at Cornell. He chose to work at Westinghouse because it was one of the largest power engineering firms, and in the company's General Engineering Department because of his interest in systems work. Only incidentally was he drawn into mathematical modeling and the use of analog and digital computing devices as a result of some of the systems problems he was assigned. Impressed by the effectiveness of these computational techniques, he continued to use them in his engineering assignments. It is easy to envision how, if contextual factors such as the Depression and internal restructuring within Westinghouse had been slightly different, Harder might have continued as a productive inventor of electrical power components and systems and not been drawn into the computing field.

Harder has acknowledged the Anacom as his most important contribution. Although he did not conceive the machine, he made such fundamental contributions to the design and construction of the full-scale version and to the management of its operation for twenty years, there is no question that he is the person who made computing an important activity at Westinghouse. The methods Harder developed for the Anacom's use, the professional staff he trained, and the cooperation he established with other Westinghouse departments enabled the Analytical Department to be an important internal resource for the company throughout most of the post-war period—continuing long after Harder's own retirement.

Anacom's value to Westinghouse is easy to visualize, though hard to quantify. It was particularly helpful in the company's internal design process and in solving difficult systems problems for customers. It is somewhat more difficult to assess the Anacom's importance outside Westinghouse. Over time, perhaps as many as thirty general-purpose analog computers resembling Anacom were built world-wide. Many of these were direct spin-offs of the Anacom, built either by Westinghouse or by McCann's firm. It is hard to determine, however, what their overall significance was.

It is perhaps useful to compare Anacom with the better known differential analyzers built by Vannevar Bush.[69] What accounts for the difference in recognition accorded these machines?[70] It is not the capabilities of the machines that distinguish them: Each could handle a wide range of abstract differential equations, and each could and did find application to problems associated with voltage regulators, servomechanisms, and nonlinear electrical and mechanical systems.[71] Nor does the number of machines built of each type provide an explanation: There were no more than fifty differential analyzers built around the world, compared to approximately thirty Anacom-like machines.[72] One reason may be that Bush's machines were built earlier than the Anacom, when there were fewer powerful, general-purpose computers, and they were used for important military applications during World War II. Perhaps more important was that Bush's machines had a high profile at MIT, where they were used by many industries, as well as by many students who went on to important computing careers. Meanwhile, Anacom and Anacom-like machines were used predominantly by engineers at Westinghouse and a few other power engineering firms.[73]

The staying power of the Anacom was remarkable, in part because of its capacity to model a complete power system. Bush's differential analyzers, which could at most represent a few circuits at a time, were all taken out of service by the early 1960s. The most nearly contemporaneous digital computer, ENIAC, which was less than two years old when Anacom was placed in operation, was decommissioned in 1955. Anacom was still valuable enough in the 1980s to be purchased by a leading engineering firm, Asea Brown Boveri, and it continued in operation until 1991. Beginning around 1954, one after another application previously carried out on Anacom or other analog computers in the Analytical Department was transferred to digital computers, but even in 1990 there remained classes of nonlinear power engineering problems for which analog machines were orders of magnitude more effective.

There are probably many other reasons why the Anacom lasted so long. Harder mentioned the fact that he built the Anacom with nice cabinets and quality components, so that it had the look of a permanent machine rather than temporary experimental apparatus. The durability and reliability of the equipment meant that it did not become a maintenance problem as it aged. The equipment was soon depreciated, and the company's money was tied up instead in its trained staff, which was already familiar with the analog approach. The organizational structure at Westinghouse, with a single Analytical Department containing both digital and analog computing devices managed by people with analog experience, also meant that managers recognized the value of analog techniques and did not have to make a choice between analog and digital.

Whatever other factors may come into play in explaining the longevity of Anacom, there is no doubt considerable truth in the statement that Anacom continued to be used because it effectively met a need in a historically neglected, but nevertheless important computer application area. Both Anacom and Harder deserve greater recognition than they have so far received.

One of Harder's great loves is sailing. Over the past forty years, he has built and repaired his own boats and made numerous boating trips, including repeated visits to his favored spots on the Georgian Bay in Canada. Thus in September 1991, at age 86, he drove from Pittsburgh to the Georgian Bay to begin another solo sailing voyage. The local newspaper picks up the story at this point:[74]

"His trip progressed reasonably well until he encountered some rough weather at Vidal Island to the east of Meldrum Bay. At this point he decided to anchor on the calm side of Crescent Island and having put out an anchor he laid down to take a rest. The anchor however did not hold and the boat moved into the rocks on Crescent Island, which is on the north side of Vidal Island.

"Mr. Harder then tried to set another anchor to hold the boat but when he was attempting to throw it out a wave hit the boat throwing both the anchor and Mr. Harder into the cold water. The water was not deep and he was able to get back on board.

"There was about 10 inches of water in the boat at this time but there was dry clothing that he was able to change into.

"He stayed on the boat for Tuesday and Wednesday and then thinking Vidal Island was the main Manitoulin he set off in his little dingy. The outboard motor on the dingy had been damaged but he took a set of oars, four slices of bread and a jug of water.

"When he arrived on Vidal Island he realized that it was not the Manitoulin so he made himself a shelter, got a white flag up and waited for help.

"Help did not come and at 3:00 a.m. on Friday [night, actually Saturday morning] he decided that he would try and get to Meldrum Bay on his own. He did have five layers of clothing on for warmth but his feet were extremely cold so he decided it was time to move.

"It was a clear night, the moon was bright and wind had subsided.

"It was not until 10:00 p.m. on Saturday evening that he finally arrived at the dock

in Meldrum Bay in his small dingy. Juhani Paronen was at the dock at the time and he could hardly believe his eyes when this elderly man rowing arrived at the dock in this little boat. After some 18 hours on the water in this small craft Mr. Harder had to be helped out of the boat and into Mr. Paronen's car."

Harder was not seriously harmed by the incident and wrote matter-of-factly to his relatives about the incident. He was able to salvage his boat, the Cozy Cub, which he was planning to repair for a return to the Georgian Bay in September 1992. Perhaps most indicative of Harder, however, were the few lines of calculations he scribbled at the bottom of the article he sent me about this incident:

11 mi. x 5280 = 58080 ft.

25 stroke/min (out of 18 hr. — say 15 hr. of rowing, 900 min.) = 22,500 strokes

58,080/22,500 = 2.58 feet/stroke

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[1] Gwen Bell, Founding Director of the Computer Museum, Boston.

[2] In 1991, while this paper was in preparation, ABB Power Systems took the Anacom out of operation and released the staff.

[3] This paper would not have been possible without the full cooperation of Edwin L. Harder. The author conducted an extensive oral history interview with Dr. Harder 30–31 July 1991 as part of the IEEE Oral History Program supported by the IEEE Life Member Fund. This interview is the basis of the biographical and much other material in this paper. Dr. Harder generously made available for my use an unpublished article entitled "The Anacom," provided photographs, and answered numerous questions. I also wish to give my thanks to David Morton, who served as the 1992 IEEE Life Member Fund Summer Intern at the Center for the History of Electrical Engineering. Mr. Morton helped with the analysis and writing of the material on Dr. Harder's patents in the electric power field. My colleagues, Andrew Goldstein, Frederik Nebeker, and Eric Schatzberg, provided useful criticism of early drafts of this paper. My graduate assistant, Jill Cooper, helped in many ways with the collection of historical information. An earlier and shorter version of this article appeared in *Annals of the History of Computing*, vol. 15, no. 2, 1993.

[4] Harder is the second of four generations of electrical engineers. His son, William Harder, is an electric power engineer who has worked for Westinghouse and American Electric Power Service. His grandson, Steven Harder, is an electrical engineering graduate from the University of Dayton.

[5] ROTC training involved summer training at a military installation. Most of the ROTC electrical engineering students at Cornell were assigned to the Signal Corps at Fort Monmouth, New Jersey. However, Harder was assigned to the Ordnance Department at Aberdeen Proving Ground, presumably because of his professed interest in mechanical engineering.

[6] Interview 1991, pp. 128–129.

[7] Harder indicated that he preferred systems work to the work of the other departments, which mainly built apparatus. He seemed to enjoy the overview afforded by systems work and the technical problem-solving challenges this department confronted.

[8] The total business of Westinghouse was $216 million but then dropped

precipitously due to the worsening economic climate. The Pennsylvania Railroad contract was the one bright spot. This order affected not only the East Pittsburgh plant, which built the locomotives but also the Sharon, Pennsylvania plant, which built the transformers and the Newark plant, which built the relays.

[9] The calculations themselves were somewhat routine inasmuch as the company had already conducted similar calculations for the Virginian, Norfolk, and Western and the New York, New Haven, and Hartford railways. The Switchgear Department had a DC calculating board for calculations to determine how big the circuit breakers should be and for setting the relays. While this DC board was adequate for 60-cycle systems, it did not give sufficient accuracy for the 25-cycle railroad electrification systems.

[10] There had been litigation involving Westinghouse, the electric utility industry, and Bell Telephone over the telephone interference caused when rectifiers were introduced. Rather than continue to litigate, the parties formed a joint commission to study and correct the situation. Harder's calculations were part of the work of this joint commission.

[11] In his oral history, Harder recounted another instance where his computing skills and knowledge of harmonics came in handy. Long Island Railroad cars traveled into New York City on DC power, while Pennsylvania Railroad cars arrived on 25-cycle AC and the signal power system employed 100-cycle AC. With the AC and the DC trains on the same track, some of the DC got into the AC transformers, which produced unusual harmonics of the 100-cycle AC and sometimes caused the signals to fail. In one instance, two trains approached head-on in a tunnel in New York City but fortunately were able to stop before crashing. Harder helped carry out the calculations that caused the railroads to change the signal power to 91⅔-cycle AC to avoid any further intermodulation.

[12] Interview 1991, pp. 47–50.

[13] In connection with this work, Harder wrote two chapters in *Electrical Transmission and Distribution Reference Book*, by Central Station Engineers of the Westinghouse Electric Corporation (East Pittsburgh PA: Westinghouse, not dated). This book was used throughout the world.

[14] The board was built by Bill Parker in the Switch Gear Department.

[15] Of course, numerical methods were again used when these problems were moved to digital computers.

[16] See E. L. Harder, "Pennsylvania Railroad New York-Washington-Harrisburg Electrification—Relay protection of power supply system," *AIEE Transactions*, vol. 58, 1939, pp. 266–277.

[17] Harder designed the annunciator systems, the load and frequency control, and the terminal boards for the Hoover Dam switchboards.

[18] See E. L. Harder, "Solution of the general voltage regulator problem by electrical analogy," *AIEE Transactions*, vol. 66, 1947, pp. 815–825, for a publication giving these results.

[19] The magnetic amplifiers were fast enough to replace standard Rototrol amplifiers in the initial stages of the systems, thereby reducing them to the two-delay systems Harder had shown to be inherently stable. During World War II, Harder designed one of the earliest magnetic amplifiers (a balanced

bias, saturated core amplifier). Gordon Brown of the MIT electrical engineering faculty had his students build this amplifier. When the war ended, Westinghouse found that it did not need this new amplifier for its commercial operations. The name "magnetic amplifiers" came into use only after the war. Harder was the chairman of the AIEE committee that developed standard nomenclature and other standards for magnetic amplifiers. Harder's design so impressed Gordon Brown that he invited Harder to join the MIT electrical engineering faculty, an offer that Harder declined for personal reasons.

[20] An oscillograph was used on the Cathedral of Learning at the University of Pittsburgh to measure the instantaneous lightning stroke current as a function of time, but it was too expensive to use at all fifty sites. A less expensive device, called the klydonograph, was used for these. To measure crest lightning current, researchers had used magnetic links, 1½ in. strips of iron placed in the field of the stroke current in a lightning rod or a tower leg. The residual magnetism was a measure of the current. In the klydonograph, about 200 of these links were placed on the periphery of a wheel, driven by a small motor. The different links coming by the recording head during a stroke gave a rough time recording of the current.

[21] In the early years, when the department had only analog computers, all of the professional employees were electrical engineers because it was important that the people doing calculations understand the applications and how they were physically modeled. When digital computers came to be used in the department, he hired some mathematicians and programmers.

[22] Interview 1991, p. 106, slightly edited.

[23] Interview 1991, p. 27.

[24] I am grateful to Harder for his generous assistance in making accurate the technical description of the HCB relay. My first attempt at describing it was replete with errors. Harder rewrote this material, and I have slightly revised his account.

[25] Interview 1991, pp. 33–35, slightly edited.

[26] The patent application was received 29 November 1937 and filed 1 December 1937. Patent number 2,144,494 was awarded 17 January 1939. The invention is described in E. L. Harder, B. E. Lenehan, and S. L. Goldsborough, "A new high speed distance type carrier pilot relay system," *AIEE Transactions*, vol. 57, 1938, p. 5.

[27] Three-phase directional relays were used because the load current in a good phase might be flowing in the opposite direction from the fault current in a faulted phase. In the three-phase relay, the fault current predominated.

[28] Harder, "An Invention Story," unpublished document, revised September 1992.

[29] E. L. Harder, B. E. Lenehan, and S. L. Goldsborough, "A new high-speed distance type carrier pilot relay system," *Transactions of the AIEE*, vol. 57, 1938, p. 5.

[30] Harder, "An Invention Story," unpublished document, revised September 1992, slightly edited.

[31] The patent application was received 4 November 1940 and filed 3 May 1941; patent number 2,331,186 was awarded 5 October 1943. The invention is described in E. L. Harder, et al., "Linear couplers for bus protection," *AIEE*

Transactions, vol. 61, 1942, pp. 214–249.

[32] The linear coupler then became a mutual reactance, and the voltages were totalized.

[33] The patent application was received 1 December 1953 and filed 29 December 1955; patent number 3,027,084 was awarded 27 March 1962. E. L. Harder, "Economic load dispatching," *Westinghouse Engineer* (November 1954): pp. 194–200; "Electrical network analyzers," *Journées Internationales du Calcul Analogique*, September 1955; "Automatic dispatch pays off," *Electrical World*, 18 April 1955; Harder et al., "Loss evaluation, Parts 1–2," *AIEE Transactions*, vol. 73, 1954.

[34] The computer could take into account a whole set of factors that affected economic dispatch: cost curves, cost multipliers, upper and lower limits on production at stations, flow in tie lines, and more.

[35] Interview 1991, p. 158.

[36] For a description see Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982* (Cambridge MA: MIT Press, 1985). These devices are described briefly in two standard survey histories of computing: Allan G. Bromley, "Analog computing devices," chapter 5 in William Aspray, ed., *Computing Before Computers* (Ames, Iowa: Iowa State University Press, 1990); Michael R. Williams, "The analog animals," chapter 5 in *A History of Computing Technology* (Englewood Cliffs NJ: Prentice-Hall, 1985).

[37] See W. R. Woodward, "Calculating short-circuit currents in networks—Testing with miniature networks," *The Electric Journal*, August 1919, pp. 344–345. A general description of analytical solutions to electric power network problems is given in Robert D. Evans, "Analytical solutions," *The Electric Journal*, August 1919, pp. 345–349.

[38] If the impedances are represented as $R + jX$, in these railroad calculations the ratio of X/R was small, which meant that the DC Board could not provide accurate calculations.

[39] See Harder, chapter 10, "Steady state performance of systems, including methods of network solution" in *Transmission and Distribution Reference Book* (East Pittsburgh PA: Westinghouse Electric Corporation, 1942).

[40] See H. A. Travers and W. W. Parker, "An Alternating-Current Calculating Board," *Electric Journal*, May 1930, pp. 266–270.

[41] Copies of the AC Calculating Board were built by Westinghouse for external use. For example, Westinghouse built one for Gibbs and Hill, the engineering firm doing the engineering of the Pennsylvania Railroad system. Many were sold to utilities all over the world.

[42] Travers and Parker, p. 268.

[43] See R. D. Evans and A. C. Monteith, "System recovery voltage determination by analytical and A.C. calculating board methods," *AIEE Transactions*, vol. 56, 1937, p. 695.

[44] See H. E. Criner, G. D. McCann, and C. E. Warren, "A new device for the solution of transient vibration problems by the method of electrical-mechanical analogy," *Journal of Applied Mechanics*, September 1945, pp. A135–A141; G. D. McCann and H. E. Criner, "Mechanical problems solved electrically," *Westinghouse Engineer*, March 1946, pp. 49–56.

[45] See E. L. Harder and G. D. McCann, "A large-scale general-purpose electric analog computer," *AIEE Transactions*, vol. 67, 1948, pp. 664–673, for a list of references to these applications of electric analog machines. See also the description of Anacom in G. D. McCann and E. L. Harder, "Computer—Mathematical Merlin," *Westinghouse Engineer*, November 1948, pp. 178–183.

[46] Harder and McCann, p. 664. The Anacom was intended to have the capacity of the electrical and mechanical transient analyzers, the servo-analyzer, and extra facilities—additional multipliers, transformers of special design, forcing functions of the independent variable, and nonlinear functions of the dependent variable.

[47] The two computers were "alike in all essential features and general design, differing only in minor matters of construction and in the exact number of each kind of element installed." (Harder and McCann, p. 664) The differences between the two machines are listed in an appendix to the Harder-McCann article. The other machine was known as the California Institute of Technology Electric Analog Computer.

[48] There were some differences in the configuration of the Westinghouse and Cal Tech models of the machine based upon their intended uses. See the appendix to Harder-McCann for a discussion of these differences. The Cal Tech machine was not designed, as was the Westinghouse machine, for use in conjunction with an AC Calculating Board. Some of the use of the Cal Tech machine was directed at aeronautical rather than electric power applications.

[49] The information about changes to Anacom was supplied in conversation with Harder and in a letter from C. J. Baldwin, Manager, Engineering Projects, Asea Brown Boveri Power T&D Company to author, 29 June 1992.

[50] Baldwin to author, 29 June 1992.

[51] E. L. Harder and J. T. Carleton, "New Techniques on the Anacom—Electric analogy computer," *AIEE Transactions*, vol. 69, 1950, pp. 547–556 (citation from p. 547).

[52] Ibid.

[53] Harder was clearly proud of his operation. He claimed that the top engineers in the company gravitated to his operation and that in his twenty years managing the operation his engineers did not make an error using the Anacom that caused a serious problem for any Westinghouse department. Part of the reason was his insistence that his engineers all have the big picture and not blindly accept results that came from the machine. Another was his insistence on good computer usage practice. "One of the bad uses [observed in one of the Westinghouse manufacturing departments] was cases where programmers tried to program something for a division and the thing just didn't work that way. They didn't understand how a shop works. They imposed the structure. They assumed that each workman when he finished his day would be willing to sit down and write down what he did and put it on punch cards and you could keep track of everything. Those fellows weren't hired to do that. They would no more do that than fly. And so the complete program was a flop" [Interview 1991, p. 104].

[54] For the 602A, the blade problem was set up as an iterative calculation. The blade was divided into ten portions and the vibrations were calculated

through the blade at different frequencies. It took two weeks of calculation—putting cards through the 602A and sorting them, over and over again—to obtain a curve of frequency versus response. Harder reports that "one good creative engineer resigned in this process. He felt that there must be a better way to make a living than standing in front of a machine for 8 hours a day, for two weeks, feeding and sorting cards, in order to get one answer. (He later became editor of the *Westinghouse Engineer.*)" ["The Anacom," unpublished manuscript.]

[55] Harder did not consciously choose to remain with IBM equipment once there were good alternatives on the market. The Westinghouse accounting department made the decision and paid part of the cost of the 7090. After that, no one in the company was willing to pay the expense of rewriting all the administrative software to consider an alternative vendor. Harder was, however, pleased with the computers and service from IBM.

[56] The strengths and weaknesses of digital and analog calculators for power applications, as of 1945, is considered in E. L. Harder, "Electrical network analyzers," International Analog Computing Meeting, Brussels, Belgium, September 1945, *Proceedings*, pp. 419–433.

[57] ABB Power Systems, Inc., Advanced Systems Technology, "Anacom III," descriptive bulletin TR-IJ-COM. The brochure lists typical transient problems done with the Anacom III: insulation requirements, surge arresters, switching surge reduction, torsional interaction, performance of static VAR compensators, series capacitor applications, operating procedures, circuit breakers, transients caused by faults, equipment design, ferroresonance, shunt reactors, and arc furnace supply circuits.

[58] Calvert was a good friend of Harder; they had shared a desk in their early days at Westinghouse. Calvert had turned down the opportunity to found a magazine with a friend at the end of World War I to pursue an engineering career. The magazine, which succeeded beyond anyone's imagination, was *Reader's Digest*. Calvert had a distinguished career, eventually heading the electrical engineering department at the University of Pittsburgh [Interview 1991, p. 148].

[59] McCann hired H. E. Criner, his collaborator at Westinghouse on the mechanical transients analyzer computer, to head Computer Engineering Associates. They eventually had a falling out and the company was sold to Susquehanna Corporation. Almost all of its staff, the company's only asset, left Susquehanna's employ within a year.

[60] Interview 1991, pp. 156–157, slightly edited.

[61] I. L. Auerbach, "IFIP—The early years: 1960-1971," in Heinz Zemanek, ed., *A Quarter Century of IFIP* (Amsterdam: North Holland, 1985), p. 87.

[62] E. L. Harder, "Financing IFIP: 'The things we can do together that we can't do separately,' " pp. 335–336 in Zemanek (cited above).

[63] On the former point, see AFIPS Board of Directors Minutes, 17 November 1969, Charles Babbage Institute Archives.

[64] Paul Lego, quoted in Interview 1991, p. 156.

[65] Interview 1991, pp. 83–84, slightly edited.

[66] See, for example, his chapters on "Steady-state performance of systems including methods of network solutions" and (with J. C. Cunningham) "Relay and circuit breaker application" in *Electrical Transmission and Distribution Reference Book* by Central Station Engineers of the Westing-

house Electric and Manufacturing Company, (Chicago: Lakeside Press, 1942); also (with W. E. Marter of Duquesne Light) "Principles and practices of protective relaying in the United States," *Transactions of the AIEE*, vol. 67, 1948, p. 1005.

[67] *Fundamentals of Energy Production* (New York: John Wiley, 1982).

[68] For example, Thomas Hughes, *Networks of Power* (Baltimore: Johns Hopkins University Press, 1983), the leading history of power engineering, ends in 1930. Richard Hirsh, *Technology and Transformation in the American Electric Utility Industry* (Cambridge, UK: Cambridge University Press, 1987) explores the later history of power engineering but characterizes much of it as a period of stasis.

[69] It is much more difficult to compare Anacom with a digital computer of its era, such as ENIAC. The digital computers led directly to commercial products, which were on the market in large numbers by the end of the 1950s. Neither differential analyzers nor Anacom-like machines were extensively manufactured. Most of the analog computers sold commercially in the post-war period were small electrical analog machines based upon the gunnery computers built during World War II. These devices were not nearly as powerful as the Anacom.

[70] Perhaps the difference in recognition was not as great at the time as the historical literature now suggests. Harder was recognized by his computing peers, as his election to professional positions in IFIP, AFIPS, and AIEE indicate.

[71] McCann-Harder, p. 182. In an unpublished article on the Anacom, Harder did identify some differences in operating principles between the two machines:

"*Electric Analog Computers* are of two general types, passive and active. The Anacom is basically a passive element computer, but did have amplifiers to represent the gains in regulating systems (no longer used).

"The active system, using operational amplifiers as integrators, adders, etc., is an electronic differential analyzer, the counterpart of the mechanical differential analyzer of Vannevar Bush."

[72] In any event, the number of technological artifacts does not necessarily correspond to the technology's importance.

[73] It is interesting to note, however, that the MIT machines were built mainly for electric power applications, as was the Anacom. The historical literature on computing gives little attention to power engineering as a driving application for the design of computing equipment—perhaps because this literature emphasizes digital computers.

[74] "86 year old man ship-wrecked 5 days," *Manitoulin Recorder*, Wednesday, 25 September 1991.