accomplished by numerically differentiating the angle measurements. Naturally, the differentiating process introduces errors in the frequency and rate of change of frequency due to the extraneous noise components in the voltage signals. Later, a process was developed for using a polynomial in time to fit angle data over a certain window and then taking the derivatives of the polynomial function. This has produced excellent results that are noise free.

These results were published in a 1983 landmark paper, "A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency, and Rate of Change of Frequency" by Phadke, Thorp, and Adamiak. This was the first disclosure of phasor measurement technique that was separated from the SCDR work.

Tony Gabrielle, head of the Computer Applications Department, left AEP in the early 1980s, and the succeeding managers were not supportive of research in computer relaying or phasor measurements. About the same time, AEP decided to move its offices to Columbus, Ohio, from New York City. With this upcoming substantial change, I joined Virginia Tech in Blacksburg. One recollection about my last days at AEP: I sent an e-mail to my new managers that the PMU idea should be patented. I received a reply the next day, in effect saying that AEP did not see any future for the technology and would not recommend applying for a patent. So much for the foresight and business acumen of the managers!

Virginia Tech

The move to Virginia Tech turned out to be very rewarding for me personally and certainly for the development of PMUs as a workable idea. It had become clear that even if SCDR as a relaying algorithm may not be needed as microcomputers became more powerful, the measurement principle developed for symmetrical components had great potential in its own right. In particular, the idea of synchronizing the data sampling at different substations evolved about this time, and the power of the synchronized phasor measurement technique was fully recognized in our group. I spent several summers at Cornell University around this time, and Jim Thorp and I developed early ideas of state measurement using PMUs instead of state estimation using traditional SCADA. The first paper (1985) on this topic, "Real-Time Voltage Phasor Measurements for Static State Estimation" by Thorp, Phadke, and Karimi, resulted from the work of Jim's graduate student.

The work on synchronized phasor measurements embodied in PMUs continued in our group in Virginia Tech, and financial support was provided by the U.S. Department of Energy, AEP, the New York Power Authority, the Tennessee Valley Authority, and the Bonneville Power Administration. I was able to assemble a team of very capable graduate students, which included Virgilio Centeno (now a colleague in Virginia Tech) and Miroslav Begovic (PES president and currently the department head of electrical engineering at Texas A&M University). Several other graduate students also participated in this development, and their research results form the base of PMU developmental work.

The synchronizing signal for these measurements was soon standardized to the evolving Global Positioning System (GPS) satellite transmissions. Although the deployed system of these satellites was incomplete at that time, it was clearly the system of the future. It remains the main source of all PMU synchronizing signals throughout the world.

PMU Prototype Development and Commercialization

Through the financial support for our research and with strong support from Virginia Tech Electrical and Computer Engineering Department, we soon developed a Power Systems Research Laboratory, and one of the most important projects undertaken in this laboratory was the development of a prototype PMU. This PMU, shown in Figure 1, was assembled from off-the-shelf components purchased from traditional computer and peripheral equipment manufacturers. An interesting side

figure 1. A prototype PMU developed at Virginia Tech in 1990s.

issue was the incomplete deployment of GPS satellites. To accommodate the loss of satellite signals in Blacksburg, Virginia, the GPS receiver had to have a very precise clock that would keep the time to within 1 µs for that interval until the satellites became visible. The cost of such a receiver was about US$20,000 in those days! One can now build a complete GPS receiver for just under US$100.

The Virginia Tech team completed the construction of about a dozen prototype PMUs by the mid 1990s, and they were deployed on an experimental basis in the substations of our funding utilities over the next few years. A great deal was learned from these early installations, and some of these prototypes are being saved by the sponsoring utilities for historical interest.

Virgilio Centeno joined Macrodyne after his graduation. Jay Murphy (CEO of Macrodyne) and Virgilio developed the first commercial PMU based on the work done at Virginia Tech. Macrodyne remained the sole commercial producer of PMUs for several years. Now about two dozen commercial vendors offer PMUs, which are being installed by utilities around the world. The development of IEEE standards for PMUs and WAMS has greatly facilitated the worldwide adoption of this technology. The PES Power System Relaying Committee under the leadership of Ken Martin (formerly of the Bonneville Power Administration) has developed the relevant standards.

WAMS and Applications of Phasor Measurements

It is fair to say that PMU installation on the power transmission networks in WAMS has become the current technology of choice among the power grid operators around the world. In many systems it is the norm to have PMUs installed at every extra-high voltage (EHV) transmission substation. Linear state estimation with phasor data is the most common first application, although the path toward complete observability with phasor measurements is often delayed until a sufficient number of PMUs are installed. Other popular applications of WAMS are improved protection and control systems with WAMS. Some of the other applications involve system model validation, post-mortem analyses of major disturbances on the power grids, and online verification of system control settings.

Looking to the Future

One could summarize the current status of PMU and WAMS development as an ongoing activity to populate the EHV power grids with WAMS. As the number of substations covered by these systems approaches sufficient numbers to accommodate advanced applications, the focus will shift from precise system monitoring to advanced protection and control of the power systems. This technology offers a path toward utilizing the power infrastructures to the fullest extent with assured security and efficiency. Catastrophic failures of the grids should become less frequent, and recovery from such events should become quicker and safe. A great many young engineers are actively participating in developing new applications of WAMS. On them rests the future of this technology.

A.G. Phadke

PMU memories

looking back over 40 years

I AM OFTEN ASKED HOW THE phasor measurement unit (PMU) idea originated and how the technology has evolved over the years. This story is intimately connected with my work and that of my colleagues over the last 40 years. I am going to recount the events of these 40 years as faithfully as I can, but inevitably there may be some omissions—in particular, the names of my graduate students and colleagues—for which I apologize in advance. Omissions are not intentional; they are just artifacts of memory loss due to advancing age.

American Electric Power

This story begins with my joining the American Electric Power (AEP) Service Corporation in New York City at the invitation of Glenn Stagg, whom I had come to know through our joint summer school teaching at the University of Wisconsin. I joined AEP in 1969, and soon thereafter I was asked to look into the technology of computer relaying that was gaining considerable attention in the IEEE Power Engineering Society (PES) Power System Relaying Committee. At AEP, I worked in the Computer Applications Department, which was led by Glenn Stagg and later by Tony Gabrielle, two of the most enlightened managers I had the good fortune to work for. I was also pleased to have the backing in this enterprise of a famous relay engineer, Stan Horowitz, who led the AEP Relaying Department. The team working on computer relaying included another distinguished relay engineer, Mohammed Ibrahim. Also joining our group were Ted Hlibka, Jerry Jauch, and Mike Price. We had a number of co-op students from various universities on short-term assignments, and among them was Mark Adamiak from Cornell, who later joined AEP and is now with General Electric Company.

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SCDR Development

To accommodate transmission line protection algorithms in the microcomputers of those days, we developed a new efficient relaying principle called symmetrical component distance relay (SCDR). The 1977 paper describing this idea, "Fundamental Basis for Distance Relaying using Symmetrical Components" by Phadke, Ibrahim, and Hlibka, won the outstanding relaying paper award from the PES Power System Relaying Committee.

About this time we were joined by Jim Thorp, a professor at Cornell University who became affiliated with our group while on sabbatical. Among other things, he developed an analysis of relay speed and its relationship to the transient components in voltage and current signals during faults. The resulting 1979 paper, "Limits to Impedance Relaying" by Thorp, Phadke, Horowitz, and Beehler, is considered by many to be of fundamental importance in relaying literature. Jim continued with our group at AEP in many capacities and was an important member of the team that developed PMU technology and its applications to power system problems. [Much later, Jim joined Virginia Tech as the head of the Department of Electrical and Computer Engineering, where he continues to work as a research professor. He remains very active in research in the field of PMUs and wide-area montioring systems (WAMS).]

I was awarded a patent for the invention of SCDR. A principal component of SCDR development was the accurate measurement of positive, negative, and zero sequence components of voltages and currents in subcycle time. Our first attempt to measure sequence components for SCDR application was to use analog circuits that would produce the necessary phase shifts in signals of phase quantities and then use the combinations of these signals to produce symmetrical components. It soon became clear that this is entirely unnecessary; one could get the required phase shifts by using the discrete Fourier transform of the sampled data. All symmetrical components could then be obtained very efficiently and without the need for any special analog signal processing.

First Phasor Measurement Paper

About this time, it was becoming clear that there were many interesting uses for the phasor measurements. One early concept was to use the phase angle of the positive sequence voltage measurement to determine local frequency and rate of change of frequency. This was

(continued on p. 93)