Algorithms & Power Systems Architecture:

Using Historical Analysis to Envision a Sustainable Future

Oral History Project

Interviewee: Bruce Wollenberg

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Interviewer(s): Julie Cohn, Sairaj Dhople

Transcriber: Temi

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***Abstract*:**

Dr. Bruce Wollenberg shares reflections on his academic and professional experiences. Before the formal interview begins, he describes experiences during and after the 2003 Northeast Blackout, including his media interviews. He mentions his positions in both in several private firms and at the University of Minnesota (UM). He describes the UM Center for Electric Energy's programming with multiple utilities in the region and the lecture series he organized. He discusses co-authoring a textbook

with Alan Wood, *Power Generation, Operation, and Control,* and later updating it with Gerald Sheblé. He notes that the book has been translated into Chinese and Korean, through the efforts of colleagues in those countries. He describes his work as an expert witness, first on a case involving the use of transformers as part of a manufacturing process and later involving methods for collecting meter data. He recalls working on a major project to implement real-time power from for Commonwealth Edison. He discusses incorporating load shedding and dispatch into real-time power flow solutions, and later work on a complete dispatch system that incorporated state estimation, contingency analysis, and corrective dispatch. He explains he next turned his attention to artificial intelligence and expert systems. He describes development of the expert alarm processor, and the need for this type of technology to prevent situations like the lack of alarms during the 2003 Northeast Blackout. He discusses integration of the expert alarm processor into supervisory control and data acquisition (SCADA) systems. He encourages the interviewees to watch the Tom Hanks movie, "Greyhound" to understand the past decision-making challenges faced by power system operators. He describes his experiences during several major blackouts, in 1965, 1977, 1984, and 2003. Reflecting on technical innovations that followed the 1965 Northeast Blackout, he recalls working on a method to attribute losses to individual utilities on a shared transmission line. He mentions postage stamp transmission fees as the alternative approach ultimately adopted. He describes introducing his industry experiences to students in his university classrooms. He reflects on his long-term friendships with several graduate students, and the loss of contact with others. He considers his most cited works, beginning with his textbook, and then, a paper about smart grids. He closes with an anecdote about how students acquire his book today, from foreign countries, where the price is lower.

Note regarding Transcript and Timestamps:

Timestamps appear in the transcript but may not align with the recording. Pauses and interruptions may have been removed, and the overall length of the recording may be reduced.

Transcript:

[*Prior to the start of the formal interview, Bruce Wollenberg shares a story about the 2003 Northeast Blackout. He has given permission to include this in the recording and the transcript*]

Bruce Wollenberg (00:00:05):

In 2003, we had a major blackout that took out Ohio, much of New York State and New York City, and a lot of Michigan—Detroit, Michigan. It was a big blackout. And I was in my office. I got a call from somebody who wanted to ask me some questions, and then somebody knocked on the door, and it's a person from the University public relations office. And she said, "we're getting a lot of calls to know if we have somebody on the campus that's an expert in power blackouts. And we were told to call electrical engineering, and the people down there said, 'it's you.'" And she said, "can we tell people to call you?" And I said, "sure." So, after I hang up, I get a call, and I was—talk about video!

Bruce Wollenberg (00:01:03):

I was on—every major television network came by and interviewed me, and the next one came and interviewed me, usually out on the front steps of the building. And my mother was visiting at that time, at home. So, I called home in between one of the—, and I said, "tell mom to watch channel such and such. I'm going to be on talking about blackouts." The next day, I got called, "would I talk to Minnesota Public Radio for—?" And I did, for about five minutes or so. And they thought, "well, maybe he does know what he's talking—." And then they called back and said, "we'd like to do a one-hour interview on the radio." So, I had the phone, and I was pacing back and forth in my office while talking to this guy. And I had some of the people from—good friends of mine from Xcel—who said they'd heard it and thought I did okay. But I wasn't the only one. There's a guy from Georgia Tech who's an expert in distribution.

Sairaj Dhople (00:02:21):

Sakis Meliopuolos?

Bruce Wollenberg (00:02:24):

Sakis. He got on one of the major TV networks, you know, he got himself even on a major TV network, and stuff. And so, a bunch of us got little cameo appearances. And I went and I told my wife, I said, "you know, there was this—who's the guy who said, 'everybody deserves 15 minutes of fame?'" I said, "there was mine. That's it. It's all gone now. I'm just back to being me."

[*Formal interview begins here*]

Julie Cohn (00:03:06):

This is Julie Cohn. I'm conducting an interview with Bruce Wollenberg on Monday, May 26th, 2025, at the University of Minnesota. Sairaj Dhople will assist with the interview, and Andrew McEniry is also participating in the interview and may ask questions. Dr. Wollenberg, during today's interview, we have many topics we'd like to cover with you regarding your work on power flow problems and how that carried forward into standard practice of the industry and several of the other projects and technologies you worked on. But we're also interested in your work broadly and how it has influenced the power industry over the decades. We'd like to begin with some introductory questions and ask you to share with us your educational and professional trajectory.

Bruce Wollenberg (00:03:56):

Okay. Education. I have a bachelor's degree in electrical engineering from Rensselaer Polytechnic Institute. I have a master's degree in power engineering, also from Rensselaer Polytechnic Institute. And then I have a PhD from the University of Pennsylvania in Philadelphia. My career, I started, when I graduated with the master's degree, I went to Leeds & Northrup in North Wales, Pennsylvania. And I was there from 1966 to '74. And then I left Leeds & Northrup, and I went to a company called PTI, Power Technologies Incorporated, which is now part of Siemens. And they were in Schenectady, New York. They were started by a large [small] group of engineers from General Electric, that started that company. And I was there for 10 years. And then when I left there, I came to Minnesota to work at the Energy Management Systems Division of Control Data, EMSD.

Bruce Wollenberg (00:05:16):

And that was in 1984. And I was there until 1989. And while I was at Control Data, I did a lot of teaching at the University of Minnesota. I started the first six months—the professor here found out that I was there and asked me that. They said, "we need somebody to teach this course." So, I taught the course, and then they asked me to help teach another course and another course. And then I taught the course based on my textbook. And then they turned to me and said, "we'd like to ask if you'd like to try out to be a professor here." So, I joined the faculty in 1989, and I was a faculty member until 2016. People kept saying, why are you retiring? And I said, "do the math."

Bruce Wollenberg (00:06:16):

My first job started in 1966, and it was now 2016. I said, "that's 50 years of working." I said, "that's enough." And so, did I tell you guys earlier today, that it came to me this morning. What really got me to

retire was the drive. The drive in—16 miles from my house. Because I bought a house near Control Data. And then it turns out that I'm working at the university. And it was a long trip in. Not bad—if it's clear weather and so forth. But if it's raining, or especially snowing, then it could be—it could get to be very lengthy. But it just got to be hard. I loved being a professor. While I was a professor, I was, for 10 years, the director of graduate studies, which meant that I was in charge of—.

Bruce Wollenberg (00:07:17):

I had to sign all kinds of forms. And was the final signature on accepting students for graduate study. I was also the director of the University of Minnesota Center for Electric Energy, UMCEE. And UMCEE had utility members. When it started out, it had a utility in Iowa, one in Wisconsin, several in Minnesota, and one way up in North Dakota. And part of the agreement when they put that together was that the university would deliver a lecture at the utility, every summer. At each utility. And so, I've driven a lot around every summer. I've driven hundreds of miles to go. Eventually the one in North Dakota dropped out and one of the ones in Iowa merged with the one in Wisconsin.

Bruce Wollenberg (00:08:30):

We would go and give lectures, and we would have unbelievable people that we would invite to give lectures. We had—have you ever met Alex Papalexopoulos? He is brilliant, just unbelievably. He came and did a complete study on how power sales are made under deregulated systems, what it's like to trade, what power trading is like. And we had many other speakers that came in. Sometimes we had equipment that we showed, or software. We had something on a computer. And sometimes Ned Mohan and I just did the lecture. We did one lecture where we said, "this lecture is going to be for non-engineering people in your company. So, send the lawyers or the secretaries or so forth.

Bruce Wollenberg (00:09:30):

And they loved it, because they said they had a lot of questions that they—they said, "I never knew what this is." And we explained a lot of that kind of thing. And anyway, that's my work career. Some of my major accomplishments—. When I went to RPI's power program, there was a professor that—he's actually an engineer from GE named Alan Wood. And he taught the course on economic dispatch and power system control. And then later on, I went back to work for PTI, and he came to me one day. He said, "why don't you come and teach the course with me?" He said, "I'm still teaching the course over at RPI." So, I helped him. And then he says, "I have some notes." And he said, "I'd like to write a book."

Bruce Wollenberg (00:10:22):

Because we had been using this book by Leon Kirchmayer. And at that point, let's say the late '70s, Kirchmayer's book was, like—30 years that it had been out. But it was the only book. It was the only book. And so, they used the book. So, he [*Al* Wood] and I made notes and used them in the course. And the next year we revised the notes and corrected them and so forth. And we had enough after five years of teaching with the notes to put them together in a textbook. And the textbook was first published by John Wiley. It's called *Power Generation Operation and Control* by Wood and Wollenberg. He [*Al* Wood] somehow, he got his name first. And that book is still—it went through the first edition, the second edition was in 1996, and the third edition was 2014.

Bruce Wollenberg (00:11:31):

And they asked me if I want to do a fourth edition. I said, "no, I'm done. I'm done." And I think, frankly, I haven't tried to keep up, once I retired. I haven't tried to keep up with everything. So, I said, "others can pick that up." But it's still generating royalties. It's still generating. So how many years is that? That's 40 years of royalties. Now granted, they peak and then they drop off quite a bit. But it's still generating, it's still being sold. They print various versions of it for sale in different parts of the world. Publishing is interesting—there's all these different versions of the book.

Sairaj Dhople (00:12:15):

How many languages has it been translated into?

Bruce Wollenberg (00:12:17):

Well, I know that, because I know the people, it got translated into Chinese. And there was an engineer that worked here that I knew MISO. But he went back to China. They lured him over there to start some program for them, in their utilities. And then I had a Chinese professor that came to work with me, and just in the two years before I retired. And so those two guys, and a third guy who, I don't think he's Chinese, and I don't think he went back to China—but those three translated. And there's a Korean version done by one guy. And he did a beautiful version and sent me a copy of the book, which has a very nice cover on it and everything.

Bruce Wollenberg (00:13:22):

He did more to dig out errata in the book. He kept saying, "what is this? What is that? Is this supposed to—?" he would find—because he'd go through every little equation and all the exponents and sub sub numbers, and he found all the mistakes. So those two, it's in Chinese and Korean. But that book has become, and it was, for a long time, it was the only such book. There was a professor—it was a professor at Georgia Tech. I can't remember his name, but somebody, we were standing around and this guy asked this professor, he said, "do you use Professor Wollenberg's book?" And he looked over. And he said, "I use my own book." So, he had a book too.

Bruce Wollenberg (00:14:22):

You know, there have been other books. But the last edition, we put a chapter in on load forecasting. And we tried to keep up with as much as we could. And in the edition, we had a third author. Al Wood died before the third edition came out, but I had a new author named Gerald Sheblé. So, there's a third name on it. So, I think it's been fairly successful. When you look at the total amount of money they've paid out over 40 years, I think, ""where did it all go? Well, it came in, in dribs and drabs, in little royalty payments. It's not a big thing. So that was a major accomplishment. The other thing that I did a lot of, starting in maybe '95, '96, I was asked to be an expert witness on a case to—doing with taxation.

Bruce Wollenberg (00:15:36):

There are laws on a lot of states' books that say if you're buying equipment for a factory and you're going to make a product in the factory, that's going to be sold, and pay taxes, sales taxes, then you don't have to pay sales taxes on the equipment. And these utilities in Minnesota, well, the main one being NSP, it's now Xcel Energy, and till, honestly, trying to remember the name, but it is a utility that's become part of Great River Energy. They each went to the State of Minnesota to say, "transformers are a manufacturing process." And when you look up the word manufacturing process, you'll often see the word "transform." It transforms steel into wire or steel into sheet or this into that. But they like to use the word "transform."

Bruce Wollenberg (00:16:40):

Here's the word "transformer." And so, they said, we should, we should—. And Minnesota, granted, they said, "yes, the transformer is part of a manufacturing process." And a couple years later, Minnesota said the entire utility is a manufacturing process. I've done a lot of expert testimony cases all over—Xcel then eventually had a branch in Denver, and I also did—in Michigan, I remember having to testify and

write an affidavit for the Michigan Supreme Court, and so forth. I just recently finished another visit to Kansas, where they're—every time they try to go for it, the Kansas utility, Kansas taxation groups is known. And then I did a lot of expert testimony work for other things. I testified over some of the way they were operating a plant down in Florida. And the most interesting, although it was very difficult, was some guys left a division that is now part of ABB.

Bruce Wollenberg (00:18:14):

They left them and went to this company called ESCA. And they blatantly took all kinds of material with them. And whenever I would see it, I would say, well, that's this and—. And it turns out you can't bring the law down on their head unless you can prove that they took material and that they then used it and took business away from the company that they took it from. So, it didn't get any place. But that was another case. And then, I did a case for a company here in Minnesota that suddenly—they had meters, and the meter would communicate through the distribution system what the reading on the meter was, so that they didn't have to—this is very great out in the country. They don't have to send somebody to, you know, cover hundreds of miles a day, and so forth. And suddenly the meters are not working. And they use what they call a capacitive power supply where—

Bruce Wollenberg (00:19:36):

I'd have to go back and to look at it again, because we simulated this capacitive circuit that—the trouble was that they bought capacitors thinking that they would be able to withstand the spikes that you'd get on the distribution system. Instead, the spike would burn a little hole in the foil that made up the surface of the capacitor. And after a while, it reduces the capacitive amount, and then it wouldn't power the meter anymore. So, this was a big lawsuit. And I was on the side of defending the company that made this circuit. But anyway, we got through it and there was a—they had a sort of a—an example trial with a sort of a jury that really—it wasn't a real trial.

Bruce Wollenberg (00:20:40):

And the jury said they would give it to the other side. And so, then they decided to settle. And I knew, I had a good friend that worked for that company that made those meters. And he said in the end, that the attorneys took all the money and they didn't get anything. I thought that was really sad. That's really one of the biggest problems with the legal system in America. But I've had a lot of experience with—I

think I know how to handle myself when a lawyer's questioning me, and asking me this and asking me that, or asking me double negatives and things.

Bruce Wollenberg (00:21:31):

You can just say, "I don't understand the question." And he has to reword it. I've done a lot of that work. The University of Minnesota is very good. They say you can have one week of—one day a week for consulting, did you know that? I didn't know that when I—and I would do some of the work on the weekends, but then, you know, if I had to take a trip, I could take the time during the week. But there's all this tax stuff.

Julie Cohn (00:22:12):

So, if you look over all of these experiences, are there one or two technical problems that really stand out as being the most challenging or the most interesting ones?

Bruce Wollenberg (00:22:24):

I sat down and made some notes the other day, yesterday.

Julie Cohn (00:22:27):

Yes.

Bruce Wollenberg (00:22:28):

Let me go down through it and then we can come back. At Leeds & Northrup, I worked on a large thing—you may have heard Anjan and I joking about it—for Commonwealth Edison, or we used to call it "Com Ed," in Chicago. And that was a real-time power flow. And then I had this—Leeds & Northrup had this contract for Middle South Utilities, which—the system was put into a control center in Little Rock, Arkansas. I never was taken there, but they had all their engineering offices in New Orleans. And so, I had the Newton power flow that Bill Tinney described in his paper. We wanted to have that for our online power flow for our systems.

Bruce Wollenberg (00:23:30):

And the real hard part was figuring out how to write the ordering algorithm. MATLAB does it for you, the sparse matrices. You've got to order it properly. And it took me about a month and a half to get the ordering. That was difficult, but everybody figured it out. I mean, people—I did this power flow for

Consolidated Edison, which had an area interchange constraint. And they could put that in, and it would adjust all the tie-flows, and was very successful. That was the, I think, first real-time power flow operating. Then I went to—also I worked on this program—you know the name George Dantzig, who was the one who invented linear programming? And he invented this technique called the Dantzig-Wolf Method, which was, you could have an LP, and it showed how to adjust the constraints in the LP so that you could have a quadratic or cubic or any nonlinear function, as long as it was a concave upward function.

Bruce Wollenberg (00:25:03):

And the LP would go in and solve the problem exactly, with those non-linear functions. I went to Power Technologies Incorporated in 1974, and one of the first things I did was—I had done a lot of work with LP at L & N and I'd done it in my thesis. And so, then I used it, and we wrote a program. Because they wanted to do the following: they'd have a reliability program, and they would take a generator out, or take a transmission line out, and they would have some overloads, and they'd say, "well, you can't count that as an outage," because the utility could adjust the system to push the power differently so that they wouldn't have an overload. So, I had an LP that would go in and do the dispatch, and it would adjust generation, and it would also do load shedding to meet contingency overloads and—I never really—PTI had a product and didn't EPRI come along and develop their own product that did the same thing. EPRI, Massoud [*Amin*]notwithstanding, I had a very bad attitude towards EPRI. EPRI would, "we did this!" This kind of thing. Anyway, I don't know. I don't say that they stole it. I think they saw it and they realized that that was a valuable thing. So, they made a product out of it.

Sairaj Dhople (00:26:41):

But Bruce, along those lines, were these all in the open literature or are these problems that you worked on in industry and it was just to sell a product or an idea?

Bruce Wollenberg (00:26:51):

They were all things—well, see, the LP thing for PTI, that was—they had a contract with a utility for one of their reliability organizations. And so, they had this thing, and it would take an outage and then it would adjust so that the outage wasn't there. And if necessary, it would show you where you had to shed load. And so, this would give you some reliability as to how, you know, how reliable or non-reliable are the loads—because of outages and having to adjust because of overloads.

Sairaj Dhople (00:27:26):

But more generally, like up until you got to the U, was it easy for you to publish some of these things?

Bruce Wollenberg (00:27:32):

Oh, yeah, yeah.

Sairaj Dhople (00:27:33):

There weren't any restrictions as such.

Bruce Wollenberg (00:27:37):

Not that I remember, no, no. They allowed me to publish. And then we went to—I was on this project for Public Service Electric and Gas. And it was a complete dispatch system. It had a state estimator, contingency analysis, corrective dispatch with the LP again. And we sold that as a product to, well, we also sold it to Israel Electric, and we sold the rights to a Swiss company. Landis and Gyr was the name of the company in Zug, Switzerland. And then Landis and Gyr became part of Siemens. It's now part of Siemens. And so, there are companies out there that are installing my software still, I suppose, or at least you know, they were for a while.

Bruce Wollenberg (00:28:38):

I went to Control Data. The thing that I worked on the hardest was, I had started reading about AI, and when I read about AI, I concentrated on what are called "expert systems." There's expert systems and neural networks. Now, today, when you hear about AI, it's neural networks. The expert systems have kind of faded into obscurity. People still use them to some extent for recognizing certain situations to act on. But we had what's called the "intelligent alarm processor." They would build these systems, and they would say, "our system can process 10,000 alarms in 10 seconds," or something. So, something would happen on the system. And the system was so electronically fast that it would get, okay, breaker opening, breaker overload, overload. And they would get 10,000 alarms and they'd come out on a screen, all these messages.

Bruce Wollenberg (00:29:47):

And I said, "what good is that? Nobody can read it. And, you know, you can't read that fast, and you need something to comprehend what's happening." And it makes a nice—you print the alarms out—it

makes a nice report. So, you can go back and analyze what happened. But when it first happens, you start looking around at what's going on, what happened, what did it do? And so, I said, it needs something that can do a quick analysis. So, we call it the "intelligent alarm processor."

Bruce Wollenberg (00:30:24):

We wrote a paper on it, and somebody gave them a prize for the paper. And in the prize, they wrote, "this is a prize for your paper on the intelligent alarm clock." But we built it, and it was installed at Xcel, at NSP, and it was there for, oh, maybe five, six years. But the problem was, the expert system has to have rules. They're called "if-then" rules. And the trouble with them is that you have to keep updating those rules. Neural networks will do it by themselves. And I've always thought it would be nice to see if you could do the intelligent alarm processor with neural networks analyzing it. Of course, they'd have to sit down and train it with hundreds of outages. But, you know, you might have all that data sitting around, you could show.

Sairaj Dhople (00:31:28):

Then would this also tell you what the corrective action had to be, or would it just be a way—

Bruce Wollenberg (00:31:32):

It would tell you what happened and suggest—

Sairaj Dhople (00:31:36):

What to do about it?

Bruce Wollenberg (00:31:37):

Yeah. And I gathered, I talked to some of the people from Xcel, and they said, "well, some of the operators really liked it and others didn't." But the cost of trying to keep it up to date just got to be too much. And they took it out. So, so much for the intelligent alarm clock.

Unidentified speaker (00:31:57):

What year was this?

Bruce Wollenberg (00:32:00):

Pardon?

Unidentified speaker (00:32:00):

What year was this?

Bruce Wollenberg (00:32:04):

In the early nineties, '91, -2, -3 in there. We did a couple other papers where we applied the rule-based AI to unit commitment and some other things. But they never took off much. And I never got into neural networks. That was a completely different topic. But Siemens was using AI to do various things long after I left the company.

Julie Cohn (00:32:51):

That's quite a range.

Bruce Wollenberg (00:32:53):

Yeah.

Julie Cohn (00:32:54):

From power flow to alarms, alarm clocks.

Bruce Wollenberg (00:32:58):

Yeah. The alarm clock. No, the alarm processor. See, it turns out that the alarm processor, when it's called upon, can take an enormous amount of the computer resources. And it turned out that the other big computer use was the contingency analysis, especially if you're trying to do AC. You try to do two iterations of—let me see, you do a P-theta iteration and a QV iteration—the two halves of the decoupled power flow—and then you stop, and you use that as a method of trying to weigh which contingencies need to be solved all the way. You try to give them a weight and order them—a contingency ordering. And that was something that we worked on and became part of Control Data standard product.

Julie Cohn (00:34:05):

So, was the idea of the alarm that, before you worked on making it an intelligent alarm, it simply—it was making alarms

Bruce Wollenberg (00:34:18):

Breaker open voltage down, open breaker, this, this—

Julie Cohn (00:34:21):

Presumably to get the attention of the operator, but the breaker really couldn't respond.

Bruce Wollenberg (00:34:26):

When an alarm came in, it would ring a—it would beep, beep, beep, beep. Or even louder. And he had to do what they call "acknowledge" the alarm, meaning he had to go and touch it with his mouse or the screen, and that meant: I've looked at it. But how can he look at 10,000 per second or something like that? It's just ridiculous.

Julie Cohn (00:34:49):

And would that, would it be normal that that would be happening constantly?

Bruce Wollenberg (00:34:54):

Well, anytime they had anything, anything happened on the system, sometimes it's major and sometimes it's just a, you know, a small—sometimes a breaker opens because of something. Some animal gets in the substation and causes a fault, and so forth. But big ones could just generate thousands of alarms. And it means it's going to take hours to figure out what went wrong and what happened. And meanwhile, the power system itself, if it has a lightning strike, and so it opens, it opens and it tries to reclose, and then it opens, it stays open, and there may be a few other things happen, and then it stops. But at that point, it may not be in a safe condition towards the next outage, and so forth.

Bruce Wollenberg (00:35:51):

So, they need to know what happened and, as much as they can, why, and what to do next. Otherwise, another contingency, another happening comes, and the system is going to drop load and put people in a blackout. The outage in 2003 was very interesting, because what happened was, the system, at about one or two o'clock in the afternoon of that day, two people made a request on their computer system, and it put the alarm processor in a loop—doing what? I don't know. But it was looping, and it wasn't presenting any alarms. And then they had a fault on one of their 345 lines, which normally produces a bunch of alarms, but they didn't see any alarms. And this started going until they had a number of major outages, that they didn't do anything about because they didn't see it.

Bruce Wollenberg (00:37:09):

I remember this one—I don't know if she was an attorney, I guess she was—and she said, "well, wasn't the fact that you weren't seeing any alarms, didn't that draw your attention?" I used to tell people; I used to say that the absence of alarms is not alarming. I said, "who gets in their car and says, 'you know, I haven't seen that orange light on the dashboard. Maybe my car is not working right?'" Nobody, nobody. So, they put systems in there to alarm the fact that the alarms aren't coming. And that was kind of a second order thing. But it was a very difficult case.

Bruce Wollenberg (00:38:04):

I was defending First Energy, which was a big utility in Ohio—in Akron, Ohio. And the stories that they told me about—what happened, eventually, some software guy comes into the control center and says, "oh, '—'" and you can imagine what word he'd put in. "Oh, —." He saw the problem. And everybody says, "oh —. What do you mean, 'oh —?'" and he says, "the alarm processor isn't working." And finally, he put it back together, and now all these alarms come out. And by that time, the system was going down. And it blacked out. It was a blackout, crept all the way to New York. And my daughter had a friend that worked in New York. And I said—because my daughter worked for a moving company, and she had this friend—and I said, "can I? Give me his number? I want to talk to him."

Bruce Wollenberg (00:39:02):

And I called him, and I said, "what's happening there? You've got this blackout." I said, "what's it like? What are—?" He says, "people are afraid that it's just another 9/11." Because this is 2003. So that's two years later. He said, "people were panicking, they're having to walk home because nothing, the subways aren't running. The power is out." A big power outage for a major city is a humongously difficult thing to get over and get through.

Bruce Wollenberg (00:39:40):

But I had another friend who determined what caused this looping. And so, the power company wrote a report. And it was software that had been written by GE. And in the report, they said that this was a fault with the GE software. Well, GE came out the next day: there was not a fault with the GE software. So, you know, it was just, it was really—maybe they shouldn't have done that. But anyway, it got out that way. But that's what happened. That, and it was that their operators were blind. They didn't see anything. The operator—the alarm processor didn't come back to them.

Julie Cohn (00:40:22):

So, when did companies start installing alarm systems like that in their control rooms?

Bruce Wollenberg (00:40:28):

What they call a SCADA system, supervisory control, which means I can cause some—I can open a breaker and send a signal. It'll open a breaker. That's supervisory control. Data acquisition just means I read all the voltages, I read the position of all the breakers and other—the temperatures and transformers, anything you want. And I bring all this data back. Data acquisition. Well, what are you going to do with all that data? Well, you pass it through something that says, "well, is the temperature too high? Is the breaker changed?" If it's changed status, those are all alarm conditions.

Julie Cohn (00:41:04):

I see.

Bruce Wollenberg (00:41:05):

So, the SCADA systems had alarms.

Julie Cohn (00:41:08):

I see.

Bruce Wollenberg (00:41:08):

And then they put the SCADA system and the control system all in one computer, or computers. But it was the same system. So, they were linked into energy management system.

Julie Cohn (00:41:23):

And that was in the '70s? Am I recalling it correctly?

Bruce Wollenberg (00:41:29):

They were building SCADA systems before then. And they were—they used, like, I think some of them used telephone logic. They would dial up into the substation and it would <makes tut-tut-tut sound> go around and read each meter, each reading, and come back. So, it could tell them that something happened. But it was very slow. And I remember it was in the '60s that they decided that it should all become electronic and that they should use high-speed digital communications. And the SCADA system

became a digital thing with this, mainly to control the substations and to see what the problems were. And that was an operations tool, that SCADA system.

Julie Cohn (00:42:22):

But it wasn't till a decade or so later that the challenge of dealing with the data became unmanageable?

Bruce Wollenberg (00:42:30):

Well, they would say, "well, we need to be able to process more alarms per second than we are now." You know, twenty alarms per second, it doesn't cut it. Okay, how about a thousand alarms per second? Well, how about 10,000? And now they just drown in it. Here comes the—you have a big event, and you can't keep up with acknowledging the alarms. And it just became—but that processing was a—to make more and more alarms quicker was good in one respect, but you needed something to tell you what the whole event was all about, what started it and, you know, so forth.

Bruce Wollenberg (00:43:21):

And I don't know what, if they've done anything different these days. People like to have alarms that, they like to say, "well, we'll sort the alarms and we'll put the bad ones down in the bottom and the important ones will go on the top and the less important—. And they had all different kinds of ways of sorting them, things like this. So, I mean, that's a lot easier to do if you just put some sort of criteria for sorting them. They could do that. But as far as I know, that's standard practice. Now it's just: have alarm processors shoot alarms to the screen. But when there's an event, operators—I mean, unless it's late at night and there's only a couple of them, but even then—usually they'll all come over and gather around and talk about it.

Bruce Wollenberg (00:44:14):

I think that's this, and that's that. And they'd have to make a decision. Do we open it here or do we try to switch it back over here? It's a lot like—you know, you see these movies of being in a ship. Have you ever watched this movie "Greyhound" with Tom Hanks? Oh, you should! You see what stress a captain of a ship has. He's on a destroyer. And he's trying to fight off these German U-boats in the Atlantic, the Battle of the Atlantic. And, somebody says, "this happened," and he goes running over, and he has to decide, what does he do? And if he does the wrong thing, does he put his ship in danger?

Bruce Wollenberg (00:45:03):

And he has to make a decision quickly because—and then they say, "well, then another torpedo's coming the other way." And "this thing's—" got to make decisions fast. It's a similar process. Submarines—that's the same when you're in a submarine. These movies show how things happen. And they start telling the captain this happened, this, and this, and this. And the captain has to process that and make the right decision what to do—full left rudder, or something like that. And if he does it wrong, the ship can be destroyed.

Sairaj Dhople (00:45:41):

So, Bruce, you've lived through the two major blackouts that everyone well, kind of, references. '65—

Bruce Wollenberg (00:45:49):

Actually. Okay. Now that you, I'm glad you brought that up. I was at RPI during the blackout in 1965, November 9th, '65, and, as I said, that was caused by a faulty relay setting in Canada for an over-current relay, for power going out of the Canadian dam, hydro station, on the Niagara River. And it opened these lines. So, all the power says, "well, I'm going to Toronto, so I'm going to go through New York State and up and around and back down to Toronto," and electrically it'll try to do that. Except that when it does that, it causes all kinds of overloads. And I remember driving home—these used car lots, had these strings of lights. They're about that big around. <gestures>

Bruce Wollenberg (00:46:56):

They're clear glass, and they're real bright. They're white, and they poured a lot of light out as I came home. During the blackout, little orange dots, which means the voltage is probably at 50% or less. And I was telling you this morning, I got home, and my wife said, "is this World War III?" And then Lyndon Johnson came out and said, "no, it wasn't." And that event, Anjan and I both agreed on this one time we talked, spurred on the whole technology of control centers doing contingency analysis and doing advanced SCADA. The business went way up after that blackout. Okay. So, then I was in Montreal, Canada, and all of a sudden, we're on our way out to dinner, and we noticed that the lights went bloop-bloop. And we said, "what was that?"

Sairaj Dhople (00:47:59):

This was in 2003?

Bruce Wollenberg (00:48:01):

No, no, this was like 1960, I think, maybe early '70s. I don't remember the dates. But all of a sudden, poof! Montreal goes out. And we went to the restaurant, and they had candles, and they were cooking on—they had stoves with bottled gas. And so, we had dinner, and we came back to the hotel, and you could hear this little generator running this little gasoline motor. They said, "you can use the elevator because we've got a little generator that's supplying power to run the elevator." And I used—I thought to myself, years later, I could have been halfway up to my floor and the generator quits, and there I'll be, sitting in the elevator all night.

Bruce Wollenberg (00:48:59):

That one was caused by these lines coming from Churchill Falls, which is way up in the northern part of Quebec, down to Quebec. And they had some problems with it. And those went out. The other thing that was a big complicated—the Montreal Canadiens were playing hockey at this big ice arena. And they had a generator big enough to carry the whole ice arena and the lights inside, and the cooling, and the PA systems. So, the game just kept going. But meanwhile, the TV stations were out. So, the game was on television. So, all the people that are hockey fans in Montreal, which is probably 93% of them, couldn't see the game. So that caused a big ruckus. So, I lived through that blackout.

Bruce Wollenberg (00:49:58):

Then I was in San Francisco [*Palo Alto, California*], visiting EPRI for a meeting. But the night before, all of a sudden, what they call the Pacific Intertie went out. They have a DC intertie, they have a parallel AC, and something went wrong, and it dropped out, and that had happened several times. So, I told people that some of the utility people would say, "Bruce, if you're going to be in our area, would you call in ahead of time so that we could be prepared for the blackout that's coming?"

Sairaj Dhople (00:50:37):

When was this incident?

Bruce Wollenberg (00:50:38):

The Pacific Intertie blackout was just—I joined Control Data in '84, and it was in '84. It was like two weeks after I started there, we went out to this meeting. I'm trying to think if I was at any other blackouts.

Julie Cohn (00:50:58):

Where were you for the 1977 New York Blackout?

Bruce Wollenberg (00:51:01):

I was living in New York State. But you know—

Julie Cohn (00:51:06):

They couldn't blame that one on you?

Bruce Wollenberg (00:51:07):

No, but the thing about that blackout was, they'd have a lightning strike, and the breakers in the substation would open, and then the software at New York Power Pool would say, "oh my, we have to regenerate all the outage factors." And they'd go through this great big calculation, and they didn't have efficient ways of just altering the matrices. They had to start from zero and just do the whole thing. And they'd barely get it done, and they'd get another lightning strike. Back up and start all over again. And they restarted several times. So, they couldn't tell what to do and what was happening. Until it happened so many times that then it cut off the connection from the—.

Bruce Wollenberg (00:52:13):

New York state has a 345 KV line. It comes from Niagara Falls across the state and down to New York City. And now it's much, much more complicated. Because it goes up to St. Lawrence Seaway, and so forth. But it's the main power corridor. And I remember seeing it, because it was so long, [*parallel to*] the New York State Thruway, from RPI to Buffalo where I grew up—we went along it and saw this 345 KV circuit. So that took New York City out. And the thing that was so bad was that there was rioting. There was—people went out and started looting stores. There was looting. And the police were trying to arrest people. And the politicians—everybody was so frustrated because they couldn't get the power back on. But it was the looting that—the outage in '65, nothing like that happened. But this did. The people said, "Hey, the power's out. Let's go loot the stores." And they did.

Sairaj Dhople (00:53:27):

Did all of these events influence your thinking about the problems that you wanted to work on?

Bruce Wollenberg (00:53:32):

Well, yeah. I mean, the main outage in '65, I came to Leeds & Northrup, and within a month, we were driving together up to visit Con Ed about what kind of computer systems we could do, to do contingency analysis and things like this. And it spurred a lot of thinking and a lot of spending, frankly. People wanted to have good ways to cope during those things. And I would say that that had a big effect all the way to 2003. After that—. I just came up with another—I remember another algorithm that I came up with that—I don't know how much use it got. I'll tell you why. But the Center for Electric Energy—the utility in Minnesota—I'm trying to think—it's in this small town to the west of us. They used to be in the Center for Electric Energy. And they quit.

Bruce Wollenberg (00:55:01):

It may come to me as I talk about it. But they said, "we have this problem where, if we have power and we're drawing power through the system, and in the meantime, somebody else is also transmitting power through the same system, and we've got losses, who is responsible for how much of the losses?" And they used to use crazy estimates and stuff like this. And I started working on that problem. And it turned out that you could solve it. I had the math on my board, like these boards in my office. And this kid comes in and he says, "oh yeah, that's trapezoidal integration."

Bruce Wollenberg (00:56:06):

And we looked at it and I said, "yes, it is. I recognize you're right. I didn't think of that." But I had an analytical way of solving that. And I could attribute losses to whoever's transactions, exactly. And so, we went out and presented that to them, and we wrote a paper. And whenever deregulation came along, there was—for example, there was a place where utilities that were in located in western New York State and let's say Ohio—and so were part of this interconnect—and they were having to pay for new transmission that had to go into the eastern part of New York and New England, because they were overloading it there. And I said, "well, here's a method. You can tell how much of their transactions actually use that transmission and how much who's using it needs to pay."

Bruce Wollenberg (00:57:13):

And, you know, the answer is, they didn't want something that was that difficult to understand or to put in. They wanted to use what they call a postage stamp method. It's like saying, "how much does it cost to send a letter from Minneapolis to Miami, versus how much does it cost to send one from Minneapolis to Duluth?" For example. You know? And it's the same postage stamp. You buy a stamp, and it goes, and

they say that's how much—that's the system. Because it's real easy to administer, but it's inequitable, really inequitable. But that's what they're stuck with right now. And they have a method. It turns out, there was this good, good friend of mine, Frank Galiana. Did you ever—remember, he was at McGill University in Montreal. And he solved the same problem, slightly differently, but basically it came down to the same method, completely independent of each other.

Bruce Wollenberg (00:58:15):

And so, there were two of us that had figured out how to solve that problem—postage stamp, which is just, it's easy. You know, you can think of, if the postal system said, "well, depending on how far your letter goes, that's how much we're going to charge you." Well, look at how, I mean, that would be infinitely complicated. Whereas a postage stamp, nope, put it on there and that's it. You know, actually, you don't lick them anymore. They're self-stick, right? You put it on and that postage stamp method is still there. That's what they use.

Sairaj Dhople (00:58:52):

So, you referenced a few different problems, Bruce. Is there a favorite one, maybe one that was the most technically challenging of all the ones that you've referenced?

Bruce Wollenberg (00:59:09):

Well, I would have to say doing the system for PSE&G allowed me to debug a state estimator and—not to just to debug the code—and then work with the engineers, finding the bad method, the reverse meters, and stuff. And realizing how difficult that was. That was probably the most challenging. But that whole system, I mean, we did a system. They had AGC, they didn't want AGC, but economic dispatch. And we did a contingency study with corrective dispatch, and so forth and so on. We really pushed it, and we had a complete system.

Sairaj Dhople (00:59:58):

And in your experience, was the problem that you considered dearest to your heart, did that also receive the same attention from the community, or did you always find that people paid more attention to things that you were like, "eh, you know, I couldn't care that much about it."

[REMOVED FROM THE TRANSCRIPT]

Julie Cohn (01:00:39):

So, I think we'll go ahead, and switch gears a little bit. One of the things that you've talked about a little bit, has been the reception of your work when you've presented a paper or shared an idea with colleagues. You've come out of industry, you went into academia, the relationship between those roles has changed. When you were in your academic role, did you find that you were welcomed with open arms when you presented a new algorithm? A new idea? Or was there a lot of pushback?

Bruce Wollenberg (01:01:20):

They knew me as somebody from industry originally. So, it was as if that never changed. Some people obviously only knew me from academia. They didn't know me as working at one of those companies. But I did all this consulting work too. And the students, the students loved it because I could talk to them about, you know, the, the practical side. Here's, for example, when we talked about circuit breakers and short circuits and overloads, I had videos of transformers blowing up, with the big yellow flames. I said, "now this is what happens." I said, "if a computer dies, you might smell something for a couple minutes." "But," I said, "that's it, and it won't work." And I said, "somebody comes by, and they take a board, and they pull the board out and they put a new one in, and they often just restart it, and that's it."

Bruce Wollenberg (01:02:22):

And the old board may get fixed, or it may get tossed out. "But," I said, "when you have a problem with a transformer, you get this." The students thought that was really wonderful. They loved having those videos of—and also videos of just showing what happens. For example, if you have current going through a disconnect switch and you open it, you get these long zzzzzzzzz <gestures> and then it goes out, you know, and things like that. So, it helped them to understand it. But I did a lot of talking about the practical side, and they just absolutely loved that. I remember the first time I taught a sophomore-level course in circuits; it was sort of like you had to do that. It was an initiation to the department, or something, I don't know.

Sairaj Dhople (01:03:20):

Everyone's done it.

Bruce Wollenberg (01:03:22):

And so, we came to what you do with capacitive, inductive, and resistive circuits. And I said, "well, now, you're all familiar with speakers." And I said, "you get a speaker, that's a two-way speaker." And I said, "how do you make the low frequency go to this big speaker and the high frequency—? And I showed them a circuit tree, and they came up and they said, "I never knew that. I never knew that I could ever understand that from what I was learning." An electrical engineer. I said, "there's a lot of practical—" Sure, but they never, you know, they never knew how that worked. So, I loved to—and many times the students would write evaluations, and they would say something about the fact that I had worked in industry and that I had a good understanding of various problems and that was helpful for them to know that. They also thought that I knew a lot about business and so forth. There was always, at least once every two or three years, some kid would come in and say, "well professor, what do I have to do to get rich?"

Bruce Wollenberg (01:04:40):

And I'd say, "well, my opinion, don't think you're going to get rich by going into a big company and fighting your way to the top, where you can make a lot of money." "Because," I said, "that's very, very difficult. Because you get so much—." I said, "start your own company. You get a good idea, and you and some other people start your own company. And if you work your tail off for several years and get the company going, and somebody will come and buy it. Then you've got money, and now you can start another company." And, you know, they thought about that for a while. American kids. That's what they think about. I'll tell you; I met this guy from Japan. In fact, I wrote a paper with him.

Bruce Wollenberg (01:05:37):

He had done some work on AI systems, expert systems. So, we wrote a joint paper, and we were at a meeting, and I had this young guy who went through the computer science program here, but he was with us because he worked at Control Data, and he had a young man with him. So, here's two senior guys with their juniors. And so, he looked at me and he said, "we hear that what Americans all want to do is, they all want to get rich." And I looked at my—and I said, "that's about right." And then we both said, "yeah, that's right." And he turned to his young guy, and he said, "what does every Japanese want?" And he says, "to have a happy family." And I just, I'll never forget that. I'll never forget that—to have a happy family. And that's what he wanted. And so, I mean, I would think Americans should be able to answer it the same way. But they all think about getting rich, getting rich, getting—. I mean, I tried to talk a successful student into coming here and getting a master's degree.

Bruce Wollenberg (01:07:03):

And what they really want to do is they want to go out and get a job and have a new car. And that's what—they will do that. They will go right out and start up a job. And then they have a job, or sometimes before they even go have the job started, they take the job offer to the dealership. And that's good enough to give them a loan to buy a new car. That's what they want. They wanted a new car.

Sairaj Dhople (01:07:32):

But Bruce, a lot of your students have done incredibly well. They have been leaders of the industry,

Bruce Wollenberg (01:07:39):

I don't know.

Sairaj Dhople (01:07:40):

In academia. How did you cultivate your relationship with your graduate students?

Bruce Wollenberg (01:07:52):

I try—like with Mark Lauby, I talked to him quite often. Ned and I both, and this was—Mark was out working, and we both put a recommendation in for him to become a Fellow. And then, I did the paperwork, and he got into the NAE. So, whenever he comes to town, he will arrange to meet my wife and I for dinner. So, we've kept very close to Mark. I wouldn't say, now there's a fellow from India. I'll meet Raja. Did you ever meet? I don't think, see, he was—

Sairaj Dhople (01:08:37):

Yeah, I met him when he was visiting here very recently. He said he had dinner with you.

Bruce Wollenberg (01:08:42):

He always comes to see me when he comes to the US. We had him to Thanksgiving dinner quite often when he was here. We used to like to have students over, especially international students, because the American students all go home. These kids can't go back to India and come back in Thanksgiving time. By the time they got there, they'd have to come right back. So, he came over, and my daughter had this specialty that she made, which was crab dip that—you take a cracker, and you put—and it's just delicious with crab meat in it. And he would write us letters, you know, a couple years later, after he was

gone back to India, saying, "this is Thanksgiving for you." And he said, "you're probably having that wonderful crab!"

Bruce Wollenberg (01:09:34):

He's a smart guy. He and his father started a business and he's doing well right now. He's trying to get connections around the world. But there's a student—but they don't all—some of them—I got an email from a fellow that I knew, and we both had the student, David Anderson. And when I saw that he had emailed me, I thought, "oh good, I can ask him where David Anderson is." So, he says, "how are you, Bruce? Have you ever heard anything from David Anderson?" Neither one of us had heard from. So sometimes they just disappear. They just disappear. And you run into them here and there. So, I mentioned Raja, he to start something on LinkedIn, which links all of—you can have a group on LinkedIn.

Bruce Wollenberg (01:10:40):

So, he wants the group to be all the students that I advised. So, I gave him a printout of it, and I said, "good luck." You know, he hasn't gotten back to me yet. But that would be interesting to be able to trade stories. I had a student who left here, he worked for Brian Stott, Sergio Brignoni. He was probably gone by the time you came, and a brilliant kid from Argentina. But he had been here on a Fulbright scholarship. And a Fulbright, you have to go back to your home country for a couple years after you finish. And so, he went back, and he came back, and he didn't—I guess he was going to do some work for Brian and suddenly he applied for a job in Chicago to work with one of the trading companies that was trading power.

Bruce Wollenberg (01:11:46):

And he knew what a lot of it was about. And he got this job, $100,000 signing bonus, $300,000-a-year salary. And in one year, that was it. They let him go. Okay. Because why? I don't know. They decided that—and then he worked in Texas for Deutsche Bank doing the same kind of trading power systems and things. And now, Amit knows him, and he said he's living in London. I don't know what he's doing. But you know, it's very hard to have long-term relationships with the students. It's difficult because they go their way, and you don't want to bother them too much. I don't have too many others'—their emails.

Sairaj Dhople (01:12:46):

But I should say that a lot of your former students speak very fondly of the time that they spent with you.

Bruce Wollenberg (01:12:52):

Yeah, yeah. We got, as I say, having them to the house and things for Christmas and New Year—Christmas and Thanksgiving and Easter. They really were happy about that, especially the students from overseas. I had this instance. I was down the block from my house at the strip mall. And I came out of the one store and I'm walking back to my car, and I hear "Professor Wollenberg!" And I said, "uh oh, who's this?" And I turned, and it's this real tall African kid. And he comes running over to me. He says, "I have to tell you, I took your course on power systems and that allowed me to get a job with Eaton, and that allowed me to have enough money to get married and have my own house." And he said, "now I'm helping my brother get over here and get his education." And he said, "thank you so much."

Bruce Wollenberg (01:14:00):

I got in the car. I was crying. That kind of thing touches you so deeply that you—the fact that you taught a course to this guy and he could lift his life up and could do so much for them. So, then there's, Swaroop, which, I didn't tell you the rest of the story. Why did I call "Swaroop"? This is a student that—he came to me, and he said, "I need a good PhD student." I said, "I've got him. It's Swaroop Guggilam." I don't how to pronounce this.

Sairaj Dhople (01:14:32):

Guggilam.

Bruce Wollenberg (01:14:32):

Yeah. And I said, "this is the guy, I don't know if I introduced you to him." And a year later he came to me, Sairaj, and said, "you were right. He's very good. This guy's very good. He was very sharp." Well, he called me way back last summer and he said, "I'm going to send you a paper."

Bruce Wollenberg (01:14:56):

And he said, "we'd like to know if you could recommend it to some people that are writing a paper on—" But they did this back in the—I'm trying to think—maybe in the '80s sometime, we did it—of the most significant papers. And we used the 20th century, so, we had everybody do it. And of course, everybody recommended several of their own papers. And that didn't work. So, somebody sat down, and they did

a good job of it. Well, now they were updating it to papers that were in the 21st century so far. He gave me this paper, and it was a paper about developing inverters that could mimic the rotating mass of a generator and react in the same way to frequency changes to try to stabilize frequency. But they would do it electronically. I mean, I thought it was a fabulous paper.

Bruce Wollenberg (01:16:08):

And I don't know what hap—I do know what happened. I got involved in something and it just tore up my time and everything. And I never got it in on time. So, I called him, oh, about a month ago, and said, "remember that paper?" I said, "I want to apologize." And he says, "well," he says, "I had a terrible automobile—" Was it Arizona or New Mexico? He was driving and his car went off the road and it flipped over, and it was really bad. And he was hurt, but his wife was with him, but she wasn't that hurt. And then you said a tornado hit his house?

Bruce Wollenberg (01:16:53):

So, I guess he says he's coming. He said he's going to be in Austin, so we'll see him in Austin.

Julie Cohn (01:17:00):

That's good.

Bruce Wollenberg (01:17:00):

But I felt so terrible. But when I told him I never got it in, they didn't hold it against me. It didn't get in. And I thought it should have, and I think it was better than a lot—They sent me, Tom Overbye sent me the paper that they wrote. I thought, "yeah, okay, this paper Swaroop helped to write, I thought towered above them." But I just never got it in.

Julie Cohn (01:17:33):

Maybe when we do the next iteration.

Bruce Wollenberg (01:17:36):

When they do the next one. Yeah. If I can.

Julie Cohn (01:17:39):

Well, let's ask you one last question and then give you back the remaining part of the holiday. This collection of interviews that we're doing will be available to any researcher in the future who wants to know about how we built our power systems from 2025 on back. And they may not be people who know anything at all about power systems. So, if a general audience could walk away with one really important thing to know about your contributions to the industry and academia and so forth, what would you want them to know?

Bruce Wollenberg (01:18:19):

The book. Because I put a tremendous amount of time into the first edition, and into the second, and especially into the last edition. Because I was the only one writing it that—well, Jerry did one chapter. I put a lot of—and before then, there were no books that were—Anjan made a comment about D-factors and things like that. I did very careful derivations of all the D-factors in the book, things like that. And you know, if somebody wants to know about that, they should start there and go into it. And if they can study the book or better yet, take a course with somebody that teaches it, that would—I'm trying to think—

Bruce Wollenberg (01:19:19):

Of course, when I look at the—what do you call—the citation indices, and the book, of course, gets thousands and thousands of references. And the papers are not always the ones that I always thought were good. I mean, I wrote a paper with Massoud about "smart grid," what is a smart grid. And that got a lot of attention because of the title. It was a hot topic. Well, let's see what they talked about here. Whereas, you know, my papers that are much more substantial about tuning state estimators, and things like that, you know, that's for the specialists. Didn't get as much attention. So, the book is probably the thing I'm most proud of. And I was saying at lunch, it's still generating royalty checks.

Bruce Wollenberg (01:20:20):

It's still generating. And Wiley has copies of it that were printed for sales in Thailand, and countries, Indonesia—and what the students do over here is they find out the price. The US price is here, <gestures> but the, the price for that paperback version, so they get some friend over there to buy them and ship it over. So suddenly, I've seen, they've come into the class, I said, "where? I've never seen that version. Where did you get it?" "Oh, I live in this place. And my friend bought it and sent it to me." So, the book itself is, I don't know, I don't think it's over a hundred dollars, but it's close—$110 or something

like that. But they want to pay $15, which I guess I don't blame them. If you're a young student with minimal funds on your hands.

Julie Cohn (01:21:38):

Well, that's, I think, an appropriate legacy to hold up. Thank you so much for your time and sharing your stories and reflections. We really appreciate it.

Sairaj Dhople (01:21:49):

Thank you so much, Bruce.

[End of interview]