Algorithms & Power Systems Architecture:

Using Historical Analysis to Envision a Sustainable Future

Oral History Project

Interviewee:	Joe Chow
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***Abstract*:**

Joe Chow, Institute Professor, Electrical, Computer, and Systems Engineering at Rensselaer Polytechnic Institute (RPI), talks about his engineering education, work with General Electric (GE), and academic profession. He describes the University of Illinois's re-establishment of a power engineering program in the 1970s, the origins of the New York Power Pool, and research experiences at GE. He discusses work on singular perturbation and efforts to develop an algorithm for computing eigenvalues on very large systems. He also describes early examining data from the Western Interconnection (called WSCC at that time and later WECC), and the paper he and his collaborators produced addressing weak systems. Dr. Chow discusses his roles at RPI, including administrative roles. He discusses developing the Power System Toolbox (a MATLAB-based power system simulation software, can be used to compute the steady-state flow of power from generators to loads) and its ongoing use. He describes his first exposure to phasor measurement units (PMUs) and his experience watching frequency changes during major events, such as the Super Bowl, and tracking disturbances on the grid. He later describes the growth of work with PMUs in the wake of the 2003 Northeast Blackout. He discusses efforts by GE and other manufacturers to train engineers to work on power systems, both internally and through university

programs. He describes research of the past 15 years on harmonics on power systems and shares a story of theory falling short of explaining actual network behavior. He discusses the contemporary concern about the increasing presence of inverter-based resources on the grid. He explains that using inverters to generate frequency signals – needed for network control – challenging. He closes with advice to young engineers to work in industry before taking an academic position.

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JULIE COHN: This is Julie Cohn, [00:01] I'm conducting an interview with Joe Chow on Monday, July 17, at the Hyatt Regency Orlando in Orlando, Florida. Sairaj Dhople will assist with the interview, and several additional people are in the room, including Manish Singh, Mahbub Bhuiyan, Daniel Molzahn, Sutanwi Chatterjee, and Rachel Harris, and some of them may ask questions as well. Dr. Chow, during today's interview, we are especially interested in your early work on power systems dynamics and control and how it has been integrated into both education and industry, but we'd like to begin with some introductory questions and general background information about you. So, if you would, please describe your educational background and your professional positions in the field of electrical and systems engineering.

JOE CHOW: Thank you, Julie. It's certainly an honor to be invited [00:02] and have some recall history, because, for example, my children and my two daughters, they were never— saw interest in, "Dad, what have you done in the past?" Maybe if I can get hold of this video and show them later on, maybe they'll get more interested even though they're both electrical engineers. So, yes, my name is Joe Chow; I'm currently an Institute Professor at the little school known as the Rensselaer Polytechnic Institute that, for some point in time, had the only electric power engineering department in the whole United States. So, I would maybe give you some context as to why I'm a power engineer. So, I grew up in Hong Kong, so I went to high school in Hong Kong, and so on. I came over to [the] University of Minnesota for my bachelor's degree [00:03]. And so, when I get to the, as you know get to, from the junior to senior year, you have to decide what you're going to study. So, I was thinking that as a foreign international, maybe at some point in time, if I couldn't get through immigration, I would go back to Hong Kong and work. I thought that the power industry there seemed to need some work. As I was growing up, power outages were not uncommon, not painful, but not uncommon, and so I decided to go and study electrical engineering. And at that point in time, it was Professor Vernon Albertson and Professor Mahmoud Rias, one is a system, and the other is machine. And what is also interesting is that I think Professor Albertson asked the graduating class, "How many of you are going to the power industry?" [00:04] I think literally, I will estimate that more than a quarter of the students who end up working for a power company.

So that's what happened, and I applied for graduate school. So, I put power in my application form, and then it just so happened that [the] University of Illinois, they were looking to restart their power program. And one of the professors picked me to be sort of the one to start a power program as a graduate student. And the effort was kind of haphazard in the sense that I was the first, and then after a little bit, John Allemang joined the group.

John has had this long career in American Electric Power, and he was instrumental in developing [00:05], refining all the state estimation software. And he was very well known for some kind of graph theory approach to observability analysis for state estimation. And this is one of the very highly cited papers. And then later on, by the time I was graduating, then the university hired Professor Pete Sauer from Purdue. Guess all you here know Professor Sauer. So, in the beginning, I was actually studying control systems because my professor, Petar Kokotovic, was well known for his singular perturbation work. And then what is also interesting is that, let me just give you a kind of background at that point. The power industry was going through a transition in the sense that [00:06] it's a tradition to keep building more and more power plants, and it just keeps sticking all the power system together, and pretty soon you have a gigantic network that you have to figure out how you want to control.

And the power community was not quite ready for that, and so what happened was that there was the 1967 Blackout. Something went wrong at the Niagara Power Plant, which is a very critical part of the New

York system, and then it triggered the big blackout at that time. And then people start realizing, Power troubles in power system are no longer local. And what happened afterward is that true to the USA government's approach [00:07], so we started a commission to study that, and so one of the conclusions was to, hey, you need coordinating councils. You can't just let the—New York at that time had seven transmission operators, and it's vertically integrated. They have their generation, transmission, and loads everything together. And then before that, there was really no coordination, so after that, New York power pool started, so I think that's probably the very first so-called system operator. But the function was very limited, it's basically the TO still scheduling based on their capability. And then the power pool, its responsibility—it just put all the dispatchers together and then try to figure out whether [00:08] it will be a secure operating system or not. And that's all they do, there are no prices and so on. And things can be pretty messed up because right around the kind of a corner of Ontario, Lake Ontario, there's this big power complex, they have nuclear power plants. And then because they're so expensive, for example, each of the nuclear power plants have maybe three or four owners. And because basically your supply of power depends on how much investment you have, basically people recognize the power is coming in from everywhere. It could be in your own system, it's externally to your own system. It goes through all the thing, and of course that the power pool operated for about until 1999, and that's where the power pool turned over into the New York Independent System Operator. And so, [00:09] that was the time and then well, how power system operates together and how the software to deal with it, they're not there and the computer was not very advanced, IBM 360 mainframe or that's—

So, when I finished my study, and I went to work for General Electric, because I had several job offers, but I decided that I'm not going to work on communications because I really didn't know anything about it. And then I don't want to work for a consultant because I did not know enough. And then I was almost offered a teaching position at a very good university. And I told the hiring professor, I don't think I'm ready yet, [00:10] so I decided to learn something more about power systems and when to work for General Electric. And I don't know where such opportunity is still around because you walk in the room, every single one of them were famous for something. It's a manufacturer, so General Electric have experts in excitation system, and the guy only work on excitation system. There are frequency control transformers, filter design, HVDC filter design. So, it was just like a little kid in Candyland, so I learned a tremendous amount from these really experienced people, and I wouldn't—somehow, I was lucky to stumble in that arena, so that was good. And not only that, [00:11] during that period of time, there [was] very little research in the university in power systems. Most of the work [was] done by the manufacturers because they had the equipment and so on. And then before I got my PhD, we actually get a contract from General Electric Company to study power system and then there's this guy Les Fink. Do you know Les?

JULIE COHN: I know the name, yes.

JOE CHOW: Because I'm sure that Les knew your father because he worked for Philadelphia Electric, and your father worked for Leeds & Northrup, I think.

JULIE COHN: Yep.

JOE CHOW: Leeds & Northrup is in Philadelphia, right?

JULIE COHN: Yep.

JOE CHOW: And he was a frequency control guy, and he had the foresight to formulate a [00:12] program in Department of Energy called systems engineering for power. Systems engineering for power, meaning that it's no longer studying components one machine at a time but that's important. So, he provided the really, the very first round of funding to universities to study power, and the amount was quite good at that time.

SAIRAJ DHOPLE: And Les was representing what agency?

JOE CHOW: That's the Department of Energy and Les's office is in the Department of Energy in the old Forrestal Building.

So, what they end up doing is that half the project, would go to the controls people, like Mike Athens from MIT and then John Zaborszky from Washington University is really the power [00:13] person, but John has a very strong foothold in the controls area as well. And remember at that time, PTI was still developing their PSSE software and we, Petar Kokotovic, John Allemang, and myself, we actually studied power system from the book of Anderson and Fouad. And so that was the kind of things that we have in those days. And it is by sheer luck, it turns out that study singular perturbation is really a method for model reduction for linear and non-line systems. And that turns out to work really well because Robin Podmore, [00:14] he was working at the Systems Control at that time. And he developed algorithms for looking into coherent generators and then through a time simulation approach and so on. And then when I arrived in General Electric, we knew all about the singular perturbation methods and so on. And Les Fink gave us some additional funding, and we started really looking into seeing the coherency issue, and we developed the eigenvalue, eigenvectors methods for identifying the coherent machines. It was interesting, the first big system that I dealt with was a 400 machine [00:15] WSCC system. In the old days it was called WSCC, not WECC.

And it was a manager one day came in and drop off this thick pile of computer printout of that system. And what it was, is it was a printout of the power flow of a particular operating condition. He said, "Hey, Joe, take a look at this, maybe you can do something about it." And so, we develop a linearized model for that system using only the electromechanical model. And then the little error, you have 400 machines, you really need 800 states, machine angle, machine speed. But we decided we just need the connection matrix, which is a 400 by 400, so called [00:16] reduce the admittance matrix. And then the question is that can we find an algorithm to compute the eigenvalue of such a big system? And the answer was not so clear. So, I had to shop around, and then I worked with this lady from IBM Watson Research Center. Her name is Jane Cullum, she's a numerical analysis person. And we managed to calculate just the slow eigenvalues in that 400 by 400 matrix. And then we develop the slow coherent machines for WECC, and then we start looking at a map and it just say, "Oh, they're all connected together." And remember, the singular [00:17] perturbation is just a mechanism of-- applying the method. I think the more important thing is to figure out what happened. How do you get the so-called timescale separation data - something slow and something fast. And then that's where we came up with the idea of reconnection. So, the fact is that if you look at how power system was constructed, it's always transmission owner have operating area and there's lots of transmissions line in between [*within*]the area. And then if you do power exchange with the neighboring area, you only need maybe a few tie lines. And then the theory worked out, and it turns out that if you isolate every single one of those so-called coherent areas, you end up with a zero eigenvalue. [00:18] That's getting really technical, but then if you start connecting with the so-called external connections, that zero eigenvalue will start getting a positive value. And this is where we get what we call the slow coherency phenomena.

So, we try to publish the result for the WSCC system, and then my manager says, "Before you do that, go and call the administrator for WSEC to tell him that something is coming up." So, we sent a copy of the paper to that particular person, and then I actually get a call, again those days it was a landline. He said, "I think what you did was just hogwash. In WSCC, we do not have weak connections. We have 500 KV [00:19] transmission lines and so on." And the answer is very simple, when you put a hundred megawatt on those 500 KV transmission lines, that is a really stiff connection. But when you put over a thousand megawatt on it, it's no longer stiff connection. It's a weak connection because you are basically, loaded up the angle of separation between the sending end, the receiving end is so large that when you try to do the linearized model, you actually see <inaudible> And so we published the paper anyway, and then what is interesting is that if you start reading transmission system papers published by BPA and all the other people in the Western interconnection, they are starting to say, weak connections. And [00:20] I would never complain about it because someone makes some impact on this. But as I thought more about it, I think it's politically correct to say that you have weak connections, because if you say these connections are very strong, they will never get another transmission line built. Because if you go to a hearing, We want to build this transmission line. And then they just say, Look at all your documents. You have all your strong connection, you have a really strong system, why do we need more transmission lines. So, it was all, for a while it was fashionable to say weak connections. So that lasted for about 10 years and then people's interests switched. And so, that was really my first contribution in the sense that something from my PhD work carried over. [00:21] In some sense, I was there, and the problem was there, and I have a tool that was applicable.

So, I worked at General Electric for about eight and a half years, and then things were a little bit slow in the sense I learned about as much I was able to get and so on. So, I decided to make a move, and my wife had a nice job in the area. So, I called Professor Howard Kaufman at RPI one afternoon, I said, "Howard, do you think you guys are hiring new faculty members because that's the only university I'm going to move." So, Howard said, "Well, we actually have a faculty member who would be retiring at the middle of the year. Why don't you come over." [00:22] It was only a drive for 20 miles, right? So that was it. So, lo and behold, I got hired, there was no advertising for the position, and it's absolute no-no, these days, right? You have to go through paperwork, but in those days, things were pretty straightforward. And so, I really like being at RPI and so I went through all the ranks, and then I became the acting department head for a while, which I didn't really quite like that kind job, but then I became the associate dean after I stepped down from the acting department head, and I interacted with the dean quite a bit. So, I became the associate dean for research, which I like very much because I was able to help the new faculty members formulate their basically not what they do [00:23] in terms of the technical area but help them figure out what the budget has to be. And try to figure out how much we can actually help them with giving them some additional funds and so on. And then I became the acting dean for one year. And then I finally realized why I didn't really like those kinds of jobs. So, I was right in the beginning, but when I was doing it, I did my best, and I enjoyed the job too. And the interaction with higher management was kind of nice and the upper management were very, very nice to me so I think I really appreciate that. And then after that, [00:24] I was very happy that we got one of the NSF engineering research centers with Professor Kevin Tomsovic as the lead in the University of Tennessee. And we have really many, many years of fruitful interaction and joint work and so on. That was just a tremendous experience towards the end of my career. So, I think that that covers the introductory questions, I suppose.

JULIE COHN: Sure. Yes. You've given us a good overview of both your non-academic and academic work. And what I find very interesting is that there was a lot of collaboration across different sectors of the industry as you were doing that work.

JOE CHOW: After I went to university, there are times where things just happen. [00:25] For example, one of the things I did was that my student, Kwok Cheung, some of you may know him, he did the power markets for many system operators, Korea and New Zealand, I think. He and I, because his thesis requires a simulation of the power system using singular perturbation and so on. And I decided that let's actually—and then at that point in time, MATLAB became quite usable. At the very beginning it was you can do, tera, much of it. It was very usable, and we developed the Power System Toolbox. Very simple machine models, at least in the beginning. And I have never really intended to develop it as a commercial product, because there was—I do not want [00:26] to develop user interface and I did not want my students to develop user interface. I think this is a grossly misuse of their capability, but fortunately Graham Rogers, when he retired from Ontario Hydro, because what happens with Ontario Hydro is that with all these, deregulation business and so on, Ontario Hydro is getting rid of their really world-renowned group of engineers. It was headed by Prabha Kundar, and Graham didn't want to move to Vancouver, because BC Hydro bought that group and folded into the - a subsidiary called Power Tech. And so, he actually took over the further development of the Power System Toolbox, and whatever that's available for free right now [00:27] he really made the toolbox a lot more usable, and so really appreciate the collaboration with him, because we actually have a technical meeting, and then he said, "Joe, I'm about to retire." I said, "Hey." And I start thinking, and that was also the right move because he was the right person to actually take care of that and dedication. Unfortunately, he didn't quite finish the development of it because he went into object-oriented programming, and he was having a really beginning of a nice user interface and so on. But at some point, in time, he couldn't keep it up, so he's-

SAIRAJ DHOPLE: Have you kept track of the number of downloads of the toolbox?

JOE CHOW: Say that again.

SAIRAJ DHOPLE: Have you kept track of the number of downloads? Do you have a sense for how many people [00:28] have used it?

JOE CHOW: Oh, it's impossible to do this, it's probably a very favorite software tools for students in China and India for a while, but now a lot more toolboxes are available. So, we still rely on using it, especially if you want to develop something really special, like the inverter controls and so on, and the positive sequence stuff, and this is what you can do. And now all the things that we developed, we open it up to the public because pretty much I'm the one who have to answer a few questions here and there, half the time, and to the very end I didn't know what is in the software anymore.

That this is a work of many students and so on, and then we move on [00:29] to the new project and so on.

SAIRAJ DHOPLE: So, it seems like singular perturbation has been at the heart of a lot of your contributions. At the time when you studied it, did you get a sense that there is something deeper here, which would apply in such a broad engineering context? Or did you just engage in it by pure academic curiosity?

JOE CHOW: Well, things never really happened the way that you envision it. I view single perturbation in the beginning as a way to get my thesis done, and fortunately at that time there were not too many people working on single perturbation. So, you want to work in these technical areas from the beginning because they are still so-called conceptual development stages and simpler problems. And then if you're coming at the end of a cycle, then it becomes a lot more complex. Try to develop extensions [00:30] and to results that were available. So, I mean the education was good. At the University of Illinois at that time, we have some really very good controls people. Now a lot of things, conceptual things I learned, they're still applicable now, but again, I just stumble into it and then now we have this book that we wrote for that method. And we didn't really say it's exclusively power system, we just say networks. And so, for a while it sort of quiet down and then suddenly the people were doing consensus, in the control area, there are these consensus analysis and so on, they start picking up on [00:31] that book. So, you can see that around 20 years after it was published, people re-discovered that and probably Petar Kokotovic was selling the book was just raising the interest and so on. But a lot of things we didn't expect, we just try to do the best we can and so on, and so that's one aspect of that though.

SAIRAJ DHOPLE: Also, Petar Kokotovic was a very controls-oriented person, right? Do you have an idea for why there was an interest in power systems from the control side when he first got to Illinois?

JOE CHOW: So, the idea of going to power system was started by this professor, Professor Mac Valkenburg. You probably heard about him, because you're from Illinois too. So, he got some funding, [00:32] and Mac was a very visionary person, and one of his claims to fame is that he wrote the very first circuit book using matrix analysis. That was a big step because if you look at the old circuit books, there's all single equations and so on from the beginning to the end. So, he wanted to start a power program, he thought that, and he looked around and say, "Hey, Peter, you are the guy." Because before you came here, in Yugoslavia, you actually work on machines, the electric machines. And so, this is how it gets started and a lot of the old engineers who have some practical experience, most of their coverage is either with communication equipment or power systems. So [00:33] Peter was very broad, and then he went on to develop adaptive controls and nonlinear controls and so on.

SAIRAJ DHOPLE: It seems like you were right at the heart of it in Illinois when they ramped up their power program and build it up.

JOE CHOW: Yes. Just happened to be the person at the time and a lot of these things have to do with luck and so on. And more recently, we have been working on phasor measurement systems. And so, the first time I seen this, was I was working with an engineer at the, NYPP, old power pool, Jim Ingleson, again, he's very interesting person, and he was showing me all the measurements that he had, [00:34] from the measurement equipment from New York. And in those days, literally it's all event-base recording because you only have so much local disk at the unit. And then every morning he go and download it remotely from modem. And I still remember he was showing me Super Bowl. So, he was showing me all the frequency traces, and he could be able to tell, say, "Joe, look." By the third commercial break, we are seeing big power swings, because by the time the third commercial break, people start going to refrigerator and so on. And there was a slight delay because the refrigerator doesn't kick in right away. And then people were flushing toilets, [00:35] and then the local water tower start having to start pumping again. And then one thing that he did is recorded the very last episode of The Survivor, there was a two-gigawatt power increase at the end of the show, because we can tell by how much the frequency drop and related to how much generation was lost or load was increased. But this is not like a generator trip where the frequency drop was very rapid, this was a much slower frequency drop because there all the time delays of all these equipment picking up the load. And [00:36] now people still publishing papers about these, and lo and behold, so control rooms these days have televisions, TVs, and for example, I'm sure that when that Super Bowl was going on, they played through the Super Bowl. And then they were basically timing to see where the control adjustments. And not only that, in the control center at the Brazilian power system ONS, and they have operators watching soccer games because this is their big thing. There are times when Brazil was playing in the World Cup in the wrong time zone people were getting up at three in the morning and suddenly you see a load surge at three in the morning. [00:37] One thing that's nice with this is the all the control centers, they share the same kind of concerns, it's not just isolated in the United States.

JULIE COHN: So, prior to access to the kind of measurements you could get with phasors, these same things were happening on the grids, but were the control centers just dealing with less fine-grained data? Or were there real problems caused by these sort of cultural shifts?

JOE CHOW: Well, I think what happens, I wouldn't know what the control center do in a sense. They can see the data, but the amount of load increase, load fluctuation is within the spec what a normal power [00:38] system can do. And so, we normally don't see drastic consequences because of the sudden, what we call these synchronized events. Just like the British watching the coronation of King Charles, there were a lot of applications before that the new world of single-phasor deployment and so on. Because in ISO New England and this engineer, Dave Bertagnolli - all these PMU people were protective relay people. Because they were the one who actually watching [00:39] the data. And Dave was good enough to look at their dynamic, those days they were called dynamic swing recorder because they don't do continuous recording, is event-based and time synchronization is not perfect. But Dave Bertagnolli can look at the frequency trace and say, "This particular unit within our area just tripped." Just by looking at the swings. Or whether there's a unit in New York that tripped, or there's a unit in Illinois that tripped, he would know but when it went that far. But there are certain characteristics, swing characteristics that he learned from looking at all these disturbances and allowances still try to pick that up. And then we have been developing all these machine-learning method to figure out [00:40] what disturbance actually happen in the power system. We are trying to basically clone Dave Bertagnolli many times so—

SAIRAJ DHOPLE: So, it seems like there were gentlemen and people just broadly across the industry that influenced a lot of the work that you did. Did you go out hunting for these people or did they find you, or how was that relationship?

JOE CHOW: I'm not sure. So, how did I get in? I don't remember how I start looking at things with Jim Ingerson and now one of the things that happened was that, so Troy actually, the capital district in New York, is [00:41] really, I would say a hot bed for power system people. So, we have General Electric, we have PTI and then New York Power Pool is right there. And then in the old days is New England Power Pool is not that far away. But it's in Massachusetts, and so New York. And part of it came from the context because we have the power department, right? So, one of the … the person who developed the first commercially viable PMU was Jay Murphy. He had his company, he was RPI grad, he worked for GE, his company, and is in Clifton Park, which is a suburb of Albany. And so, he got a project with [00:42] TVA, because TVA is doing a, what they call hydro upgrade, so the idea is to -

[Pause]

JOE CHOW: There's not a whole lot to learn in the universities. General [00:44] Electric and probably Westinghouse and so on, they develop materials for learning power systems. And it's important because they are selling power equipment. If you don't have educated users, it is difficult. You want people who know, who not just follow instructions and press this button, press this button, turn this off. They understand something. General Electric published a series of books by their own engineers, and I still have multiple copies of them, and then Westinghouse did the same. And so, and not only that, General Electric, from time to time, they send, then allow universities to recruit [00:45] from them. For example, one of the relay and surge phenomenon engineer was—oh, geez, the name was just—this Harold Peterson. He was well known GE and then he later on moved to University of Wisconsin and be a professor there, and he retired around 1978, or just when I would start working for GE. And so, this is the way how the power industry try to manage the supply, because you do need good power engineer professors to train the students, so you can have, right? And at that time, I think Purdue had a very strong power program. So, GE had, when I [00:46] was there, and before I arrived, they hired many really good PhD and graduate students from Purdue. At that time, they have Paul Krauss, Danny Carroll, Jerry Heydt, and so they have a broad coverage and <inaudible>. So, they have a broad spectrum of coverage. So, we can pick it up from where we just left off. What was the question?

JULIE COHN: I think you had just talked about Dave Bertagnolli—

JOE CHOW: Oh, okay.

JULIE COHN: And the need to clone him, and the TVA project.

JOE CHOW: The TVA project. That's right. And then somehow, I was asked by the power department professor, I was not in the Power Department at that time. I was in the [00:47] electrical engineering department because I still wanted to do control for a while. And then, it turns out that Jay Murphy, who got the project with TVA, he took his PMU down to the power plant and do the measurement because the upgrade project is to actually try to increase the power rating of the generator with modern technology and so on to maybe 10, 15% beyond what they are now. And that requires rewinding the rotor not the stator, but rewinding the rotor to make the turbine more, to make the power generation more efficient.

So, this is really the first time I saw a PMU. And PMU, if it's not connected to internet, it's just recording device. So, I was able to see the data being captured and the native data that was being captured [00:48] at that time was 2.88 hertz, kilohertz, so 48 data points per second and so on. And what was really interesting is that we were doing all the measurements, and then Jay was saying that, “How come that have strange waveforms being measured?” It turns out that when they did the generator trip, they had to physically open the relay, pressing a button. And apparently the circuit breaker in the relay had broken parts. And so incidentally, we figure out a hidden problem for them. And then the next day, the engineer who worked for us, at TVA is T. W. Cease, and he had been attending the power meeting for a long time, except perhaps after the pandemic. And so, on the next day, people were there fixing the relay, because it's a [00:49] easy fix, and if you don't fix it the next time, it could have caused severe damage to a generator. So that was my first encounter with PMU. And then I got interested in the PMU meetings, and so I started attending the Power System Dynamic Measurement Committee. And in those days, the meeting consisted of mostly four people, it's Jim Ingleson, myself, Dick Shulz, who I have worked with at General Electric. Later on, he moved to American Electric Power, AEP in Columbus. And AEP happened to be an early installer of the PMUs, because the microdyne PMUs were in four systems, New York, installed by NYPA, New York Power Authority, AEP, and TVA [00:50] and also the west coast. The West coast is BPA and Southern California Edison and so on. So, he was there because he had this interest, and from time to time, just a few, one or two other people. After the blackout of 2003 and then suddenly that working group ballooned to over a hundred people. So, they were some of the lean days of power system measurement. And then people start seriously looking at the PMU data and we actually learned how to really make use of it. So that's mostly some of the research I'm still doing after 15 years or so because we were the very first group who have a massive amount of PMU [00:51] data, and so in the beginning, instead of PMU repository and so on, TVA was picking up data from New York and TVA. And in those days was Ritchie Carroll, and they were having their rudimentary <inaudible> down in TVA. And I sent a couple of students to download these hurricane measurements and big disturbance and so on. And then we have to bring external drive over. And then, the data was so voluminous, and they actually have to offload them into CDs and [00:52] so on. So basically, they were retrieving the CD and download it into the external drive that we bought. And so, it was Luigi Vanfretti and Andrew Armenia who went down there, and after two days, they came back because we thought the two days was good enough to offload the data. Ritchie had to send the data to us later on in a week or so because it took that long to get the data. And it was really hard, then you start discovering all the quirkiness with all the data that we have. So ever since we have to try to make a little dent here and there and so on. And I think we have got to the point where we are analyzing ambient data, because in the beginning, we were only doing disturbance data and we didn't know how [00:53] we don't have the concept of looking at data. But the work done by Montana Tech, Dan Trudnowskie and University of Wyoming, John Pierre, they were extremely helpful to us. So let me say something about things that didn't go right.

JULIE COHN: Please.

JOE CHOW: So, I was a fresh engineer in GE, and GE was very nice. They put the new engineers in all kinds of projects, whether they're ready for or not, and I was putting the project very interesting, it was measuring the harmonic impedance, looking out from the Celilo HVDC system. The idea is to put in a power <inaudible> and a probing signal in Celilo, and then you look out [00:54] into the system and figure out what the impedance of the system looked like so that you can design filter more vigorously because, HVDC system generate a lot of harmonics. And you do need the filters, the fifth, seventh, 11, and 15 and so on.

So, they were doing the recordings, and I wasn't there doing recordings. And one of my mentors at GE was Bill Price, he was well known in the power system computing. And he was later on well-known for doing load modeling and extended simulations. So, they did measurement, and then I have the job to analyze the data. Basically, the job is to calculate these [00:55] impedance circles. So literally as you increase the frequency, you should see these the <inaudible> network like this on the impedance part. And so, the whole premise came about because there was a French engineer who published a paper doing such measurement. And I think his name, last name is Crevier. And so, I read the paper and did all the calculations that was in the paper. The lower harmonics was fine, it was really a tracing up like this, but the high harmonics was just not really very good, not what we expected. [00:56] So, it was EPRI project, the funding end and we wrote some papers and so on, and it was done. And later on, about 20 years about maybe 15 years later, and I was on a consulting project to do the same thing. And I told the guy, "Wow, we published this paper." He was aware of it. I just said, "No. I think we need something more than what we have done." So, I was worrying about it say, if we did the same thing as we have done before, we'll probably end up with some silly answers. So, after I thought about it, and then I said, "Geez, I think what happened is that we never really thought about the inherent harmonic sources in the network." Which [00:57] can be modeled as a voltage source, at different frequencies. So, what do we do? It turns out that the answer was quite simple. I'm just an equation—I was just an equation guy, and I'm always would be the equation guy. We just have to have so many equations to deal with, and so we decided that we need to find out the inherent voltage source and the answer was very simple. All you have to do is to measure the ambient signature.

So basically, what you do is that you just—you don't put any probing signal in the system and just measure what you can see. And then what you do is - and then you do the measurement [00:58] with the probing signal and so on. Then all you have to do is subtract the whatever the harmonic source that's out there, the ambient harmonic source. And that worked out really well. And then, later on, I look around and I think that this is not unknown in a sense. That other people have thought about this, and I don't know what the paper that we later on dug up was about, but in power electronics now when you remember that one of the stability conditions is really measuring the impedances. At harmonic impedance, so that you know whether <inaudible> criteria and so on, when you will go unstable. So, you need to measure the impedance looking to the system, and this is the way to do it. That you have to do an ambient measurement and then put in a probing signal and [00:59] do the other calculation. But hey, as a new engineer, and the only thing I knew was equations so there's no reality of what goes on. And I read the paper, and I did exactly what the paper told me to do, and so we end up in the wrong path. I'm glad that I could solve that problem it always bugged me in a sense that even, I don't know, and I'm a dynamics person. I'm not a network impedance guy, a circuit analysis person. But it bugged me, and I'm happy that I managed to figure out what was wrong, even though it was 15 years late.

JULIE COHN: It's interesting because it sounds like there's more than one example of when the theoretical approach met [01:00] the physical operations, and there was a mismatch, not necessarily because the theoretical approach was wrong, but because there was something wrong with the equipment, or, how the theoretical approach considered all the pieces of the physical.

JOE CHOW: Yeah. I suspect that that maybe that the French engineer knew about it, but he didn't say it. The power industry have issues like this. You tell people all the wonderful things that you can do, but you don't tell them a hundred percent of the detail. You tell them about 80% of detail, you have to work to figure out what the other 20 percentage is.

JULIE COHN: That's interesting. Yeah. So, I think we are probably getting close to the end of our time together. I'm just curious if, as you look ahead to electrification in the coming years [01:01] do you see your approaches to technical problems still applying? Do you think that the next generation of engineers will need to come at their problems in a different way? What are your thoughts about that?

JOE CHOW: Well, I think that we certainly have much more powerful tools that we have now, than we had, in the seventies and eighties. And then we have a much bigger research group now. And we have worked on much larger problems. But let me just say something from the dynamic side. I certainly think that power electronics will play a very significant role, [01:02] and I think that the issues caused by power system, by the power electronics on the power system should be very manageable if everybody just come to the table and talk to each other. And in the power industry, remember that a lot of times if you operate as a small system, all the controls that you have designed for it will work well, things happen when it's part of a bigger system. Now you are affecting your neighbors or your neighbors, they're affecting you, so you really have to take that into account. And then, a lot of the operating issues are very innocent in the sense that it's not in the spec.

And [01:03] yeah, you can't really blame the supplier and the many times the supplier won't, if you inverted manufacturing and solution provider, you really don't want to get entangled into the network problems. You want to make sure that, and literally, the only thing that you can guarantee is that we can operate well in certain conditions. When the external system is working very nice, when you have some emergencies, we have certain options that you can use. And it's up to you to figure out which options you want to use. Because manufacturers don't want to do system studies, because that, again, the liability part is important. And if you [01:04] stick to your little area, you can always say, "Well, we meet all your specs. What - the issue that you are looking at is not my problem." But it is interesting, do we— the new inverter base resources is still, I would say that really in the last five years that you start really having to pay attention to it. And the AC power system have literally 70 years to work on the problems up. And remember that system frequency has always been a very useful signal, it simplifies everything for the controls that you have to do. And it's a signal that's measure - that can be measured everywhere. And if you look at PMU [01:05] measurements of system frequency over the whole you see the Eastern connection, in general, they're almost the same everywhere. But with converters, they're a lot more challenging, especially if inverter wants to generate its own frequency with grid-forming approach and so on.

That requires a lot of really, either ingenuity, or a lot of insurance policies like putting in synchronous condensers and relay STATCOMS and so on. And in the overall scheme of things, they are probably very affordable to do. Because the expensive part these days is building a transmission system or building a generation plant with a lot of big footprints. A lot of these [01:06] voltage-support equipment takes up very little space. For example, in Austin, if you familiar with Austin, in downtown, there are three chimneys, rising from the river. And there used to be a power plant there. And so, they got rid of the power plant, sure, but then they run into a voltage problem in downtown. So, they installed static var control, and the static var control is a tiny part of the footprint. But they kept everything there, just maybe it's fine. So, for people who are worrying about inertia and so on, and I really don't think that with careful analysis, I think the AC system will still [01:07] work fine, and as long as we still have these hydro units running around, and we do have many of them around. And then, so we'll never get down to inertias less than 20% of what we have now. And a lot of the system now operates from time to time, short period of time where they have more than 50% renewable resources, and as long it's not for time being, as long as nothing happens during that period, everything seems to be still good so—I would say that there's really a lot of opportunities to actually work on that. And this is almost like in the sixties and early seventies where the power engineers [01:08] were still considering how to make the interconnected power system work well to the point where the people are learning how to really incorporate the renewables, the inverter base resources.

JULIE COHN: Thank you. Anybody have any final questions you'd like to ask?

SAIRAJ DHOPLE: Well, if you had to leave a word of advice for the next generation of power engineers, could you offer some?

JOE CHOW: Well, let me speak from my own experience in the sense that if you work for a power company, and most likely your work will be very interesting, dealing with problems and so on, there will probably be no lack of interesting work to do. And the nice thing about it is that [01:09] the power companies are very good in continuing education because there are a lot of classes that you can go in GE, PTI, and what's not so common then. Now for those professors, which I'm one of them I believe that they should really try to acquire industry experience in addition to a lot of the new faculty member have actually national lab experience. One of the things that you can do is go and spend sabbatical leaves. I spent a sabbatical at New York ISO, 13 months after they deregulated. And at that time, Chuck King, who was the vice president at that time—Marija may mention him and gave me two [01:10] possibilities. When I asked him for sabbatical leave, "You can work in planning, or you can work with market design." And I said, "Planning, I already did that a lot in GE, so give me market design. I don't know anything about it."

So that was very interesting, and I actually get to see the control operators. I spent a whole morning sitting with the day-ahead engineer to clear the day head market. Looking through all the steps, and I just spend several hours sitting with the real-time balancing engineer that go through all the things and so on and fortunately those days were calm days so, nothing much happened. And I still didn't really manage to establish [01:11] a research track, when I went back to university to do markets, because that was probably still a little bit early. But then after that I was really very, very busy with the PMU stuff, so I didn't pick up market until more recently where a finance professor asked me to help her with some of this stuff. So, get the practical experience, because they will point you to really new areas and things that also helps you to actually get the industry perspective. And then the other thing is to try to be different.

So, for example, voltage stability has been around for a long time, and I look at [01:12] everybody that's working on it. I just say, "I didn't get in at the very beginning. I was busy doing other things, and then should I be doing it?" I should say no, because probably there are all, a lot of good techniques around. And mainly computing the voltage collapse point, and then much later we were doing a <inaudible> impedance calculation using PMU data for BPA. It's very interesting, but then literally we have to give them a voltage margin as an answer, and I was thinking about, "How do you actually do that? It is impossible to use any of the commercial software to do it. First of all, it's humongous. Then second, if you use a continuation method the convergence is going to be always an issue." [01:13] So we thought about it a lot, and then Scott Ghiocel and we came up with defining the voltage collapse bus into a new kind of bus type in a power flow program. So, we know, for example, for a generator, you can do the <inaudible> for PV. So, we have power and voltage, and you have the load, which is P and Q, and you have the swing bus, which is a fixed angle, but whatever, we have the power you need to absorb the losses.

And then we thought about this, we added a new bus type to solve this, because the power with the voltage collapse problem is a singularity problem because the admittance [01:14] matrix gets to be not invertible, so you don't have a powerful solution. And it is ranked deficient by one in most cases. How do you do that? How do we move that deficiency? What we did is that we just say the bus with the voltage collapse that's likely to happen. We are going to fix the reactive power and the angle, so we call that AQ. A is for angle and Q, and what happened is that it removes that singularity, it became a solvable power, and then it's quite natural because all you have to do, remember that you have a fixed angle in the swing bus. [01:15]

Now, how do you keep picking up more power from the generator? All you have to do is keep increasing the angle at the bus, and it has the natural effect of pulling the power out. And then the voltage will keep dropping and so on. That's no problem because you can solve it right to the voltage collapse point. If you specify the angle to be too much, then you don't have solutions. It was rare that there is still a little gap that we can make a contribution after all the study that people have done, all the great work that they have done, figure out, continuation method. What is the Newton step that you took, what is the slope that you have to do and so on. And it's again, 20 [01:16] years too late. People already have spent so much time refining their continuation method, they're not suddenly going to change to AQ bus method.

JULIE COHN: Unless they need to.

JOE CHOW: Well, people may change.

JULIE COHN: Dr. Chow, thank you so much for taking the time to share all of these great stories and perspectives with us.

JOE CHOW: Well, I, let me just say that I've been really lucky, I just happened to step into the field just when some new thinking was needed, and I was able to make some contributions to it.

JULIE COHN: Greatly appreciate it.

JOE CHOW: Thank you. Thank you for this opportunity.

SAIRAJ DHOPLE: Thank you.

JOE CHOW: Sorry, I did all the talking.

JULIE COHN: That was the goal. We like for you to do all the talking.

[End of Interview]