**Algorithms & Power Systems Architecture:**

**Using Historical Analysis to Envision a Sustainable Future**

**Oral History Project**

Interviewee: Christopher DeMarco

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***Abstract*:**

Dr. Christopher DeMarco discusses his educational and professional experiences. He describes studying with Fred Schweppe and George Verghese at MIT and working on a wind energy project on Cuttyhunk Island near Martha's Vineyard, then studying with Art Bergen at UC Berkeley and moving into work on voltage stability. He refers to incidents of voltage collapse in the 1980s in Japan and France that triggered interest in this field. He reflects on grid expansion in the post-war years and especially an interest in a "smart grid" in the early 2000s. He explains that increasing computational power aided in modeling significant numbers of grid scenarios. He describes the transfer of these technical innovations from academic research settings to real-world applications. He mentions an early 1970s experiment on the Turkish power system that provided a benchmark against which to test analytic models. He recalls

an analog simulator from the MIT lab, and notes that his own work has been almost entirely within the digital domain. He underscores the importance of ensuring that software represents equations, and that said equations are reasonable representations of reality. He offers additional detail about the Cuttyhunk effort to integrate a synchronous wind generator with diesel generators on an island system. He explains efforts to accelerate and decelerate the wind turbine to achieve greater control. He describes early efforts to address cybersecurity on the grid. He mentions his own skepticism regarding the 1990s move to restructuring and deregulation. He explains that movement toward distributed control of power systems increases the importance of addressing cybersecurity. He describes changes in research funding, from individual investigator projects to large group projects. He discusses how algorithms become standardized. He describes the intersecting work of control theory, circuit theory, and voltage stability. He mentions several venues in which these cross-disciplinary topics were discussed. He looks ahead to the changing context of grid stability, with distributed generation, and what he terms the "democratization" of system control. He offers an anecdote related to his own electric vehicle and an EV charger. He explains that the future holds challenges in terms of both organizational issues and the physics of control. He mentions a project for the Federal Energy Regulatory Commission to establish a scientific basis for defining the bulk power system. He describes recent work in the private sector. He closes with encouragement to future power system engineers to attend to the merging of analytic models and statistical estimation to solve power system problems in ways that were not possible in the past.

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:***

Julie Cohn (00:00:00):

This is Julie Cohn. I'm conducting an interview with Christopher DeMarco on Friday, July 25th, 2025 at the University of Wisconsin-Madison. Daniel Molzahn, who is in the room, and Sairaj Dhople, who is joining online, will assist with the interview. Others are in the room with us and may ask questions later in the interview. Dr. DeMarco, during today's interview, we are especially interested in your early work on power systems stability and control. And in addition, we'd like to learn more about some of the first work done on the intersection of physical cybersecurity and grid stability. But first, we'd like to ask you to tell us a little bit about your academic educational background and the professional positions you've held since you were in school.

Christopher DeMarco (00:04:06):

Very good. Well, welcome to Madison. Nice to have you here, and happy to participate. In terms of my own background I was educated, took my undergraduate degree in electrical engineering and computer science at MIT, finishing up in 1980. At that point, conducted undergraduate research work with Fred Schweppe and George Verghese that prompted my interest and focus towards power systems, including an opportunity to work on a wind energy project and subsequent summer job, although job may be a misnomer, on the island of Cuttyhunk off of Martha's Vineyard. So, that was an intriguing introduction to energy systems and their wide range of applications. From there I went out to Berkeley to pursue graduate studies, admittedly imagining that I might take a master's degree and leave at that point. But got lured into the academic world as I progressed in projects there.

Christopher DeMarco (00:05:19):

Working with Art Bergen as my PhD advisor and as a close co-advisor of Felix Wu. And indeed, the first summer project I embarked on there was a follow-on really to some work that George Gross had done at PG&E on optimization of pumped storage hydro resources. So, a topic that I think resonates again today as storage is being optimized throughout the grid. So, from there proceeded into work on grid stability, and particularly looking at an emerging topic in what was termed "voltage stability" in a mathematical sense, really, you could say just a different direction by which the grid could lose stable operation, but it brought in a different set of concerns and possible control actions. And ultimately, at least in my work, greater attention to stochastic effects that might influence the stable operation of the grid and help you characterize, sort of degrees of stability. Finished up my PhD in December of '84 and arrived here in Madison in January of '85, where, outside of some visiting appointments elsewhere, I've spent my career since

Julie Cohn (00:06:54):

What was happening on power systems in the early 1980s that made this voltage topic of importance to researchers.

Christopher DeMarco (00:07:04):

Yeah, there had been a few significant incidents around the world, and the terminology that was used was "voltage collapse." And again, from a more formal point of view, I would say what you were seeing was a particular set of quantities in the grid operation that, shall we say, ran away in an unstable fashion in this case, particularly the voltage magnitude. So viewed from the home user, the 120-volt magnitude that you expect at your outlet, you could think of as sort of declining and then falling off a cliff. And that had happened on a grid, if not grid-wide, certainly over a large footprint. an incident in Tokyo, an incident in France in the early '80s, and growing concern of vulnerability to these problems here in North America as well. So that prompted a good deal of attention to this voltage stability issue.

Christopher DeMarco (00:08:07):

But I think it fit within a larger context that was a driving force at that time of what people termed "grid security." Which was, prior to 9/11—and the much more, shall we say, malevolent action of humans—viewpoint of security, was just a general view of, "oh, add a particular operating condition in the grid." There are many things that characterize desirable operation. Historically, the economic side had been a dominant feature. The security was an attempt to bring in kind of all of the features that made the grid robust against, again, inevitable random disturbances that are part of any large, geographically exposed infrastructure like the grid. So stability was a key point of that, but it was meant to encompass a little bit more than stability, sort of the ability to maintain desirable operation in the face of a range of credible changes, disturbances, even human behavior. The Tokyo voltage collapse that I alluded to was often associated, people felt, with just a large increase in customer load you know, driven by, shall we say, coordinated human behavior and social events.

Julie Cohn (00:09:31):

So, things like a soccer match?

Christopher DeMarco (00:09:33):

In simpler terms. Lots of stuff turned on at once.

Julie Cohn (00:09:35):

Yes. So, was the scale of electrification changing significantly at that point? Is that why these issues became more evident or a greater concern? Or were there other changes happening outside of power systems that made this more—of greater interest?

Christopher DeMarco (00:09:57):

I think in a sense you were seeing use catch up with a lot of the capital development that had been quite rapid and pronounced in the post-war years through the 1970s. And I think by the 1980s, you were seeing some of the large-scale expansion of the grid. Talking about a worldwide system it's hard to generalize. But broadly, in a lot of developed economies, beginning to slow in capital development as usage of the grid, certainly continued to increase at still pretty significant rates, perhaps slowing a little bit after the oil crisis, the '70s, and greater attention to conservation, but still significant growth driven by population, other needs, with a physical infrastructure that was growing less rapidly. And I think that brought added attention to what the buzzword of the early 2000s might have been to operate "smart," you know, how to make a "smart grid." Not a term I love, but you catch the drift.

Julie Cohn (00:11:14):

Yes. So, looking back on those years, what would you consider the most important technical challenge that you tackled?

Christopher DeMarco (00:11:23):

I think trying to view a stability problem in a very large-scale system, while treating stochastic inputs. So really trying to bring to bear a range of tools in stochastic stability. And at that point at least, a good deal of attention to finding analytic formulations that, shall we say, gave some additional structural insight in addition to, shall we say, just a select computational result. Because I think part of this backdrop with what was often termed "security assessment" was that one really wanted a sense of how the system would respond over a very large number of scenarios. And at that point, at least, the computational tools were very adept at tracing out and predicting performance with respect to a specific specified scenario, played out in time. And increasingly even then, computational power was growing in a way that could let you look at significant number of scenarios, but never enough to, shall we say, span the space of all the possibilities one wanted to consider. So it really was looking for structural features that would let you come up with indices that could measure a degree of robustness, a kind of degree of survivability, to maintain desirable operation over a very broadly described set of possible disturbances. And in the early work that I did, often describing those in a stochastic fashion in terms of variation in load, and then down the road to some degree, treating changes in grid topology as well.

Julie Cohn (00:13:18):

Were the utilities following your work pretty closely?

Christopher DeMarco (00:13:21):

I would certainly say the voltage stability work in general attracted a lot of interest from the industry. The transition from algorithms and academia to industrial application was often, not surprisingly from the standpoint of academics, frustratingly slow. But the idea certainly percolated and had impact again, often looking for ways to bring these into commercial packages. I think in many ways the most effective means of technology transfer at that point in history, and maybe remains true today, was placing PhD students in positions to have impact in the various companies that produced grid software.

Julie Cohn (00:14:09):

Was that the primary pathway for information exchange then, through your students who went out to work in various institutions, corporations?

Christopher DeMarco (00:14:22):

I wouldn't necessarily say primary pathway, but I think the ultimate path of impact.

Julie Cohn (00:14:27):

Interesting. Yeah. What about other settings like IEEE meetings or—?

Christopher DeMarco (00:14:33):

Definitely. I think you know, those were often the ways in which one could, shall we say, whet the appetite of those who might be the ultimate end users of these ideas. But to actually get things put to work, in an industry that has to be very careful about the reliability of its software and kind of the verifiability of all the steps it takes, many of the things that might be recommended by these methods might involve, shall we say, tradeoffs of operating slightly less economically to gain what, by some algorithmic measure, was an improvement in this robustness of security. You really can understand that the utilities wanted to be able to justify that those kinds of improvements that are showing up in the algorithm, quote/unquote on paper, or realistically in the software, justified the costs that they might incur in perhaps a slightly less economic operation at a particular point in time.

Julie Cohn (00:15:38):

I think that's been a conundrum for the power companies from day one.

Christopher DeMarco (00:15:43):

I think in a large infrastructure like this, and, but I think you see this in a number of problems in society, you are oftentimes taking steps to protect against what are really very rare events. And as rare events, they don't lend themselves well to traditional statistical estimation tools. You can't do a great job predicting the probability of a blackout tomorrow based on the history of on the order of scores of blackouts throughout—of any major scale—throughout human history. So you're often trading off things that you don't have a very precisely defined probability distribution for, against things that are very visible operating costs hour-by-hour, day-by-day. Week-by-week.

Julie Cohn (00:16:35):

So within the academic world, were there researchers at other institutions, or perhaps even here, whose work was in competition with yours, whose solutions were different, and you had to navigate some sort of process of determining which solution made the most sense?

Christopher DeMarco (00:16:56):

Certainly this voltage stability issue attracted many researchers around the world. I think fairly friendly competition, and I think, perhaps I'm glossing over a little bit, but at their heart, many of them were, shall we say, getting at the same foundations, just from slightly different perspectives. But there were a number of efforts as years went by to make, shall we say, objective comparison of—because many times these methods took the form ultimately of some sort of index, some sort of scalar or low dimensional vector numerical measure of vulnerability. Either a single measure at a point in time or, or measures roughly speaking sort of in different directions of motion of the system along predicted paths in the future. So you could take those kinds of measures, then, oftentimes with simulation tools, because experimenting with the actual system is frowned-upon, come up with a large number of scenarios that might ultimately—in a given simulation—ultimately progress to a point of failure, and see how well these numerical measures performed in predicting that progression and sort of catching you at a safe point.

Christopher DeMarco (00:18:25):

And that, importantly, providing information about potential corrective measures to improve the operating condition.

Julie Cohn (00:18:34):

Did you want to jump in?

Daniel Molzahn (00:18:35):

Maybe one quick follow-up on that is, so, I'm curious, do you know of any instances where people did do experiments on the actual system? We've heard some stories before, from other interviews, but they were a ways back before, I think, this voltage stability, the topic was really focused on

Christopher DeMarco (00:18:53):

The most dramatic that I recall, just because I leaned on it and it was several years old at the point when I was looking at it in my PhD. So it now qualifies as ancient history. I did wonder if you might start this interview with carbon-dating of your subject. I'm grateful you didn't do so. So, going way back in the Turkish system, there were a set of experiments where, in essence, the system was within a limited footprint, but still a non-trivial area was sort of run to failure in this voltage collapse sense. So voltage was allowed to decline until they ran away the system with an outage. And that became sort of a good benchmark against which to test analytic models.

Daniel Molzahn (00:19:46):

So did everyone have access to the, like—is this an experiment that—?

Christopher DeMarco (00:19:49):

The amount of recorded data given—I think the actual event dated from the 1970s—you can imagine the density of the recorded data was pretty sparse compared to modern standards, but it still gave you something to compare against. And even without precise numerical measures sort of qualitative behavior that you could say, "oh, am I qualitatively getting that same class of behavior?" You know, voltage stability was notable in that the often—oftentimes, the ultimate path to decay was maybe some oscillations initially, but ultimately a really kind of first order response of exponential decline. And that's qualitatively different from the kind of electromechanical stability that had dominated a lot of the studies historically, where almost inherently, given the nature of the system as a bunch of lightly damped oscillators interconnected, you almost always saw more or less damped or undamped sinusoidal behavior that was the qualitative behavior versus this sort of exponential decline that was more pronounced in voltage collapse events. So even if, without precise numerical data, you could at least say, "did we pass the smell test of getting the right qualitative behavior?"

Daniel Molzahn (00:21:18):

So maybe a follow-up on that as well. So, when people started seeing this very different sort of response, how—presumably the sort of modeling approaches that have been used in the past were no longer appropriate or at least no longer complete enough to address that behavior. So how did you go about, or what was the, how did the community go about figuring out what needed to be modeled in this sort of new stability—?

Christopher DeMarco (00:21:44):

That certainly was one of the key questions. But I think some aspects of it were fairly obvious. And frankly, what had been left out, historically in models, was well recognized. It was just a long period of time where people convinced themselves, "what we're leaving out is not relevant to the phenomena we care about." And in power terms that was predominantly representation of voltage magnitude behavior, and reactive power demand behavior. And importantly then the various control systems that influence voltage magnitudes. So, in many of the, at least simpler transient stability models that tried to capture the select mechanical oscillatory behavior, the control systems regulating voltage magnitude were either very crudely represented or all the way to the extreme, just represented these perfect control systems that held, at least at some points in the grid, voltage magnitude to a perfect set point.

Christopher DeMarco (00:22:46):

And that's a common trick in studying dynamics that I think engineers benefit from, in a way that natural systems rarely do. We design some parts of our system with the whole goal of holding certain quantities to constants. And if we can pretend that those systems are doing a perfect job, suddenly our modeling the rest of the system gets easier. "Oh, here's a quantity where we don't have to introduce a complex set of differential equations or perhaps control algorithm representations." We just say, "oh, that variable, we're doing a perfect job. We'll hold it constant." That became less true when studying voltage stability.

Julie Cohn (00:23:30):

Sairaj, I wonder if you have any follow-on questions at this moment?

Sairaj Dhople (00:23:35):

Chris, just following up to something that Dan mentioned, a lot of our interviewees have also commented on the ease with which analog computers and network analyzers, back in the day, provided more intuition about the operation of the grid, and how that intuition was lost once we went to digital computers. So maybe taking a step away from actual experimenting on the grid, do you have any comments about how much we trust models and simulation today versus tinkering with the real network? And whether more insights are on offer if we did translate, or if we did transition our efforts to doing more hardware-type demonstrations?

Christopher DeMarco (00:24:24):

But having come of age in my research and the very first steps in the late '70s, already at that point software tools were dominating predictions of stability. And for example, the MIT lab in which I worked with Fred Schweppe, George Verghese, [*Steve Umans*], and others, for a long time had an analog simulator that recreated a small group of synchronous machines coupled through a network in a small model. That system was being retired about the time I came of age. And the piece of software that I inherited and then tinkered with at that point to represent wind generation in this Cuttyhunk Island project had been based on that analog system and, shall we say, validated against it.

Christopher DeMarco (00:25:40):

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But I was already working in the domain of digital tools. But I think your question is a valid one. There are sort of two aspects that we have to be very careful not to lose. One is the fact that any of these mathematical representations that then get represented in a software algorithm, I think the algorithms for the most part do a very good job of representing the, shall we say, the predictions of the mathematical equations. Though even that is subject to validation. And the nature of numerical integration algorithms has advanced enough, we don't have to worry too much. But it still pays to check that even, does the software represent the equations? But more fundamentally to your questions, are the equations a reasonable representation of reality? And realistically, at any point, that subset of reality that is the phenomena in which we're interested.

Christopher DeMarco (00:26:43):

It's an overused quote. It's in, I think, not even an exact quote from his original paper, but I think many folks have heard the comment from George Box, who was a longstanding contributor in statistics here at UW-Madison, who says, simply, "all models are wrong. Some models are useful." And I think we do have to be careful in, shall we say, validating that usefulness against a physical reality. We've made reasonable efforts of that in the power area. But given the sensitivity of our system, both historically, long before sort of cybersecurity and malicious actor concerns, just the nature of a critical infrastructure that serves the public good, people are very sensitive about playing around with it. And that sensitivity has only grown with the rising nature of cybersecurity concerns and other things.

Christopher DeMarco (00:27:51):

We've all seen it as academics in the dearth of data that was available in the period post 9/11, when suddenly everything was critical energy infrastructure. And what for many of us, we viewed as sort of the most mundane physical measurements on the system were viewed as data that could not be released, for fear that it might enable malicious actors. So, in short, I think we still have a ways to go in doing a better job validating our models against physical reality. At the large-scale network model, that remains a challenge. But as measurement technologies proliferate, the growth of PMUs and really the growth of all kinds of high-bandwidth measurement devices, we have a much richer data set to compare against. And I think some of what you may be alluding to is also are what I might call sort of "end devices."

Christopher DeMarco (00:28:55):

The power electronics that often sit at the nodes of the grid are growing in complexity. We are, shall we say, experimenting with many different representations of how they might be controlled. That was at least in part, I guess, the subject of a workshop here over the last week. And carefully characterizing those devices in ways that allow for tractable mathematical representation that then feed into models, algorithms, and software that predict larger-scale behavior is important. And I think there is an important Achilles heel to watch for there: that you may represent behavior of an isolated component, seemingly very well, in that isolated component, and not always adequately capture its behavior when interconnected in a very large-scale system. The neural nets are the sort of poster child for that. Each individual neuron is an exceptionally simple, easy to characterize component. And yet the behavior you get out of interconnections of huge numbers of these things can be very complex and difficult to predict. And the grid, I think, is perhaps not quite as severe a problem. But still a very large interconnected system. Any one component, we can do a great job characterizing. But how the behavior emerges when we connect hundreds of thousands, millions, potentially billions of these devices together still remains a significant challenge.

Julie Cohn (00:30:35):

Do you have a follow-on question, Sairaj?

Sairaj Dhople (00:30:39):

No thanks, Julie

Christopher DeMarco (00:30:41):

Please go ahead.

Sairaj Dhople (00:30:46):

Oh, I said I was quite satisfied with your response, Chris. Thanks, Julie.

Julie Cohn (00:30:51):

Okay. Thank you. Okay. Can you tell us a little bit about working with Fred Schweppe and the other colleague you mentioned? George?

Christopher DeMarco (00:31:05):

Yeah. I was back as an undergraduate at MIT, so I was certainly a neophyte, but I was very grateful for the kindness they both showed me. And as I may have alluded to, in landing me an extraordinarily cushy summer job to follow on my undergraduate degree. Both wonderful individuals. The late Fred Schweppe is certainly a legend in the field—originator of state estimation. And really one of the first individuals to have the insights to bring sort of local feedback control based on frequency to end-use devices on the load side. A topic that we still perhaps have not brought anywhere near the fruition that Fred envisioned, but I think is something that will be a more and more powerful contributor down the road. But I distinctly remember, MIT runs a January break period.

Christopher DeMarco (00:32:13):

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So in this January break period, I had to be back because I was participating on the track team, and we were required to be back and actually work hard for practices. But they also ran a bunch of academic seminars that you could pop in with sort of no obligation and importantly no real work to do.

Christopher DeMarco (00:33:09):

So, Fred Schweppe ran a seminar on the nature and control of the grid. I think this was probably January of '78. And I, right there, was hooked and found the topic fascinating. I think that was probably about at the time he was composing what has become kind of a legendary article in the field, "The anatomy of a blackout." And he spoke on a number of those topics that caught my interest, and I chatted with him afterwards and knowing that I would have to write an undergraduate research thesis at some point, started exploring the opportunity of contributing in his lab. And things followed from there. Slightly later, George Verghese arrived as a new faculty member at that point, coming in from Stanford. And Fred suggested that I might work with George. And George was, is, just a wonderful person that really, it was a delight to work under his supervision. And I will credit him with just a beautiful care in, language and composing academic articles that I fear I've not been able to live up to his standards, but was always inspired by that. And tellingly have since been inspired by a set of beautiful books. His brother is quite a recognized author, Abraham Verghese. And if any of you have not experienced his books, I highly recommend them. They're lovely.

Christopher DeMarco (00:34:48):

But that then led to an undergraduate project working with this team that was integrating a wind turbine on this isolated island power grid on this little island of Cuttyhunk, trying to integrate a wind turbine with a group of diesel generators that had been the historic production on the [*island's*] grid. Here, I'll confess another of my pet peeves years later, the term "microgrid" and the idea that microgrid was some sort of novel field of study became quite popular. I think microgrids have existed for ages, and there was one of them, there on Cuttyhunk. Any island community that was isolated from the mainland has operated a microgrid since, undoubtedly, at least the teens of the 20th century. So Cuttyhunk was just another example of that. But bringing in a wind turbine with a set of control systems—quite different from the way wind has evolved today.

Christopher DeMarco (00:35:54):

It was a synchronous wind generator, so had to rotate at a fixed speed. It had controllable ailerons, basically at the tips of the blades. You could change the aerodynamic properties of the blades with a feedback control system that then coupled to the electrical control systems on the generator. And the trick was how to operate that in a stable fashion against these diesel generators, because indeed it was subject, in high turbulent winds to instability effects. And I think I will credit that with at least some of my subsequent interest in bringing stochastic elements into stability analysis, because it was very clear at Cuttyhunk, in more mild, steady winds, no stability problem existed. But when you got this more stochastic excitation of the system through highly variable winds you created unstable modes that made the system run away and have to shut down in ways that, as you can imagine, made the islanders quite unhappy.

Julie Cohn (00:37:00):

Were you able to draw on other fields of mathematics or science to figure out how to abstract that behavior?

Christopher DeMarco (00:37:12):

You know, in fairness, I will go back. My interest in engineering was certainly driven, as a kid, by a love of fixing things. Which usually involved taking things apart and breaking them first. And I think, certainly on Cuttyhunk, that willingness to be a little bit of a jack-of-all-trades with mechanical, electrical, hydraulic systems—and a willingness to not be afraid to break things, because that was almost inevitable—probably played as large a role as any mathematical element. I actually think my career may have been largely misguided, and I'm not sure who to blame for this, but I think as I progressed academically, this sense that working with one's hands and doing more mechanical things was somehow looked down upon. And that working more mathematically brought a greater level of prestige. I was unfortunately suckered into it, and that's what led me to the mathematics. I probably should have stuck fixing small engines, but—.

Julie Cohn (00:38:20):

But then we wouldn't have the stability modeling and control opportunities that we have.

Christopher DeMarco (00:38:26):

Yeah. But your lawnmower would run great.

Julie Cohn (00:38:29):

Yeah.

Daniel Molzahn (00:38:31):

One quick follow up on that. You mentioned using synchronous generators for the wind turbines. We had talked to somebody, and I forget who exactly, which interview it was, but had mentioned that—that was the first model that people used was synchronous generators or first—,

Christopher DeMarco (00:38:44):

And important to note, directly coupled then to the grid. So, you had to operate at synchronous speed.

Daniel Molzahn (00:38:50):

Right. Not through power electronics devices. And from what—I forget our previous interviewee—had mentioned that it was sort of known at the time, or at least his perspective was, it was known at the time that this wasn't necessarily the best way to do things, that if you had induction generators—or some other approaches could be more effective, but that the power systems engineers wanted the synchronous generator because they understood it. Do you think that, I mean, I'm likely misquoting the previous interviewee that I'm not remembering, but would you agree with that sentiment or—?

Christopher DeMarco (00:39:25):

There's some of that, but I'd also be a little careful. I mean think about the state of power electronics in the late '70s. This system, by the way, did involve a power electronic system off to the side that I'll mention in a moment, but I don't want to say it was the state-of-the-art. You certainly could have pushed a bit further, but a lot of things were still thyristor controlled. The speed of the devices was not great. I think in some ways, in fairness, we were still waiting for the power electronic technology to catch up a little bit in terms of its power handling capability, its speed of switching, and really moving away from the thyristor device, which, if you remember, just gives you sort of one point in the waveform where you're allowed to switch. You really needed some of those advances before you could start shall we say, decoupling, presumably still sinusoidal output from whatever class of generator you were using, coupled directly to the rotating blades—to decouple that sinusoid in, in frequency and other characteristics from the sinusoid of the grid, needed a little higher-class power electronics than you might've offered at that time.

Christopher DeMarco (00:40:46):

What I do want to highlight about the Cuttyhunk project and the folks I worked with who—that was a little company founded by, I think you could say, a rich hobbyist who liked the idea of wind, and, not coincidentally, his family owned half this island. But he collected initially a group of engineers who were not highly trained academicians, and they really made a lot of progress. These were very capable, seat of the pants engineers. And in keeping with my previous comments, at least one of them, I think, had worked in a Jaguar repair shop prior to going to work for this company. But you know, when they started encountering more sophisticated control problems, went knocking on doors at MIT, found Fred Schweppe, and went on from there. But one of the clever ideas they had, that we used to joke about, the control system that changed the aerodynamic properties of the blades, literally was just the last, probably 15% of the blade length, could change its pitch.

Christopher DeMarco (00:41:59):

You know, you didn't want to move the whole blade. That was a big mass. If you have any sense of the aerodynamics of a rotating propeller as it comes up to speed, shall we say, most of the action is happening out near the end that's traveling at the highest speed. So just rotating a small portion of the blade could have a big impact on the aerodynamics, but keep your mass low. But that was done hydraulically. So inherently a fairly low bandwidth, slow control system, the electrical instability effects were happening at a higher bandwidth, higher frequency. Some of that could be compensated for back at the diesel generators, but there was a limit to how much you were going to mess with what really were just governor control systems, pretty crude, on big Detroit Diesel-Allison motors. So the alternative was to create a power electronic system that was just thyristor-switched resistors.

Christopher DeMarco (00:42:59):

We would dump a certain amount of power in exchange for control capability. So when the wind would get more stochastic, you'd get these fast variations. Admittedly you were, quote/unquote wasting energy. But I think it is a lesson here today that you have to be careful what you think of as waste. If you're gaining the ability to continue operating this system by stabilizing it, and your alternative is to shut the system down, is it truly a waste to send 5% of your energy at that point, truly, to waste heat? One could hope with future implementation of these ideas, for example, even if it is just resistive heating, lots of good uses you could put that to. And it was a high bandwidth switching of this resistive heating that would be held to some nominal point of demand. So you could reduce that demand if you needed to slightly accelerate the wind turbine, you could increase that demand if you needed to slightly decelerate at a much higher bandwidth than the blade tips allowed. And part of what made the project that I worked on fun was really thinking about, "oh, how do you blend together–what portion of bandwidth out here in the resistive control versus more steady state control, that in a control system sense could go down to DC with these ailerons, and get a stable system out of that."

Daniel Molzahn (00:44:31):

Did that eventually lead to Chaitany's dissertation?

Christopher DeMarco (00:44:35):

Yeah, certainly. The inspiration was there.

Julie Cohn (00:44:38):

Can you please explain or ask the question again?

Daniel Molzahn (00:44:42):

Sorry. One of my office mates, when I was here was Chaitanya Baone and who was one of Chris's students and was using batteries—

Christopher DeMarco (00:44:52):

Took this concept to much higher levels of sophistication with a range of technologies available today, including batteries playing a big role on the grid. But the idea that—you don't want to run the battery down long term. You'd like to make that pattern be set, coming back to our earlier comments, by more economic concerns of how to best use that storage. But if you're willing to use a little, shall we say, 5% band of fast variation around that charging strategy, there's a lot of good you can do with that control action. And yes, my students carried on with that idea.

Julie Cohn (00:45:34):

So a through-line from the 1970s to the 2000s.

Daniel Molzahn (00:45:39):

Yeah.

Julie Cohn (00:45:40):

Very cool. Sairaj, did you want to jump in at this moment, or—?

Sairaj Dhople (00:45:47):

No, I don't have anything to add on to that.

Julie Cohn (00:45:49):

Okay. Thank you. So you spoke a little bit about the issue of cybersecurity. And I have to assume this became an issue for power systems relatively recently within the long history of electrification, but that perhaps you were involved early on in thinking about the intersection of cybersecurity and grid stability.

Christopher DeMarco (00:46:18):

So, here, my first foray into looking at cybersecurity issues as they coupled to grid stability was really on an issue where, well, I guess the history is not yet complete. I could still be proven right. But in the 1990s, I have to admit that I felt restructuring and deregulation was a profoundly misguided idea, doomed to failure. Because at least, as best I could see it, you had a system in which we were choosing to quote/unquote deregulate, I think more realistically change the structure of regulation to bring in more competition for generation in the grid. But most people seemed to agree that the transmission system would remain a regulated monopoly. Now, I'm no expert in economics, but it is my rough intuition that anytime you put a highly competitive system, tightly integrated with a regulated monopoly, you tend to get the phenomena of, shall we say, socialize the cost, privatize the benefit.

Christopher DeMarco (00:47:29):

I don't want to suggest that that could possibly have happened among the well-meaning folks in the power grid, footnote Enron, but I was a skeptic. And one of the ways that I thought I would make my case that taking this relatively deregulated approach to generation, but coupling it through still a regulated monopoly system in transmission, arguably we've only made those monopolies bigger with ISOs, was to show that through control actions an individual generator could, roughly speaking, create problems for its competitors. So the problem that I looked at was, could an individual generator change its control system in such a way that it would maintain stable operation, but create unstable oscillations in other generators on the grid? And turns out a single generator cannot, you need at least two points of leverage to create this. But with two or more generators, to put it in mathematical terms, it is a problem in Eigenvector placement.

Christopher DeMarco (00:48:48):

And there are well-developed techniques for changing the dynamics of a system. Eigenvector just says you're going to change the shape of an oscillatory mode, so it's felt more in these components of the state vector, i.e. at these locations of generators. And you couldn't completely isolate, shall we say, all of the bad actors from the effect, but you could minimize it, you could leave some of them completely unaffected, and yet their actions were destabilizing others. This, of course, stopped deregulation and competition dead in its tracks. The rest of the industry saw the light of day based on my papers. Or, well, no, actually, no. Actually, I think I was presenting at a conference and one esteemed colleague said that only a criminal would suggest ideas like that, and these were deeply misguided things to bring forward in the power grid.

Christopher DeMarco (00:49:46):

Then eventually I was at a DOE meeting where a woman took me aside and pointed out that her previous position had been with another three initial agency that remained unnamed, and she thought this was a really bad idea, and could I stop this? And then 9/11 came along, and for a while, at least, I did stop this.

Julie Cohn (00:50:08):

Did you pick it up again later?

Christopher DeMarco (00:50:09):

I did. At, at some point it seemed the cat was out of the bag, and it was worth, particularly as we begin to think about distributed control—perhaps all the way down to end use consumer devices—control is inevitably a two-edged sword. You know, it can bring many benefits distributed out among many players, but, if, for example, every car home charger has its own feedback system determining the exact rate at which it's going to charge that battery again, coming back to earlier points, if it can operate in certain bandwidths, oh yes, a bunch of those hacked to operate in concert could certainly induce instabilities that, for example, could trip a large generator offline or groups of large generators.

Christopher DeMarco (00:50:58):

And as we've seen in previous blackouts, if that happens for certain classes of large generators, it's a long time before you bring those back up.

Daniel Molzahn (00:51:09):

So when you were first working on this in the '90s—I feel like today there'd be more of a recognition that we should understand the potential vulnerability so that we can mitigate that.

Christopher DeMarco (00:51:18):

Yeah, nobody's taken me aside recently and, well, no, people have called me a criminal, but for other reasons.

Daniel Molzahn (00:51:25):

But at the time, there was just not that recognition—that we're sort of better off not knowing that this could happen.

Christopher DeMarco (00:51:32):

I think it ran so—in fairness, you had an industry that was so dedicated to reliable, secure service to its customers, and devoting all of its energy to, shall we say, the positive steps to ensure that this idea that there could be benefit in temporarily playing black hat, I think was still a relatively new idea among folks on the grid side.

Daniel Molzahn (00:51:59):

Interesting.

Julie Cohn (00:52:02):

It's interesting that looking back even much, much further back to the origins of electrification, most of the concerns along those lines were about how a bad actor would take advantage of an electric power network to do something bad, but not to the network itself.

Christopher DeMarco (00:52:27):

It is true that the fairest criticism coming back, my earlier point, might be that you're much more likely to see bad actors in the form of Enron. Let's make a lot of money, rather than let's disadvantage my competitors, which is a much riskier and, in a sense, longer term strategy, oh, will I benefit down the road because I've made my competitors look unreliable and they've been put out of business. Probably not the first action somebody goes after.

Julie Cohn (00:52:59):

Have you continued research that has been embraced and funded by interested agencies in the field of cyberattacks and grid stability?

Christopher DeMarco (00:53:15):

Honestly, no. I think it is still the, shall we say, the positive steps. So, the optimization of operation for maximum economic benefit has tended to attract a lot more attention.

Julie Cohn (00:53:35):

So, moving back again to some of the work that you did in the latter years of the 20th century and the beginning of this century, who were your primary collaborators on your work? Was it mostly graduate students or people outside at other institutions? Was it utility people?

Christopher DeMarco (00:53:52):

So I think you really have seen a change in the nature of projects and funding. In the earlier years, a lot of the work I did was funded by National Science Foundation, and at least at that point, through the latter years of the 20th century, individual investigator awards were still quite common. And several of mine fit that bill. Or small groups—two, three investigators then—with significant groups of graduate students, as well, tended to be the model. And quite honestly, I think that was the pattern I grew up with and was comfortable with. As we transitioned into the 21st century, I think you saw growing interest in sort of bringing to bear larger group efforts across multiple campuses. And I participated in a number of projects like that, enjoyed it. But if I'm being honest, I don't think it was ever my most natural home turf. I think other folks were better at that than I was.

Julie Cohn (00:55:03):

What about in terms of—you describe it as less comfortable—but what about in terms of productivity and applicability for industry?

Christopher DeMarco (00:55:12):

Yeah, I think I certainly understand the motivation of funding agencies and the policy of the government in general, that you often can bring a broader range of talents and then sort of—what's the term that's used—spanning this valley between more academic development of ideas and ultimate commercialization. So I think, in those collaborations certainly, we did take steps in that direction of thinking more carefully about how algorithms might be ultimately integrated into commercially viable code and the like.

Julie Cohn (00:55:54):

Can you reflect a little bit on how algorithms became standardized over time, in use?

Christopher DeMarco (00:56:05):

Certainly I think some of this happened on the academic side, the sifting and winnowing, if you will, as various techniques get tried. Sometimes, as we alluded to earlier, a given set of algorithms or techniques seeking to solve the same problem would actually be brought to bear on some testbed problems. And you'd see certain ideas emerging as the, if not dominant, sort of bringing the field in that direction. But I think ultimately in the power area, with a fairly small number of vendors responsible for the large software packages that go into control centers, and perhaps even further consolidation of that with the development of ISOs in the U.S. in the 21st century period, you would have sort of a clear funneling effect as ideas would make their way into use in the ISOs. And even today you still see some variations, some experimentation of somewhat different approaches across different areas of the country, sometimes dictated by, sort of, the nature of problems in a given area. The Western U.S. having somewhat different characteristics than the East. But sometimes just the different ISOs, sort of, maybe a little bit of internal pride in going their own way and believing that they've got a technique that is superior to that of their neighboring ISOs. But even that process tends to see some consolidation over the years.

Daniel Molzahn (00:57:49):

So, maybe as a follow-up on that, earlier on, you had mentioned when you were first starting at Berkeley, that you had worked with PG&E and with George Gross's group there. We've heard from a few of our other interviewees working with that group in particular. So, it seemed like that was quite fruitful or impactful for you at the time, was there, as sort of the nature of those collaborations changed over? Is there a group like PG&E from that era that—?

Christopher DeMarco (00:58:24):

Well, I think there were certainly select, I'll say, utility entities that were significant participants in research. And PG&E would've been one example. Bonneville Power another. I didn't have direct experience, but I think TVA, for other folks, played that role. But then, as an umbrella, and really in those early years and into my early years here in Madison, I should recognize as well the Electric Power Research Institute. EPRI played a significant role as being a vehicle for kind of, shall we say, collecting industry viewpoints on what were relevant ideas, and then actually serving essentially as a funding agency for projects. And that continued. Several of the early projects I worked on here in Madison were EPRI-funded. Some of those had an international footprint as well.

Christopher DeMarco (00:59:29):

I have fond memories of collaborations with folks at CEPEL, which, at that point, was the research arm of the Brazilian national utility that was facilitated by EPRI, looking at—one of the big projects was control of multi-terminal DC lines. Anticipating at that point—it was prior to the construction of the multi-terminal DC line from Canada into New England, but Brazil was also working on multi-terminal DC and thinking about ways to best coordinate the control of those systems with the AC system surrounding it. It was a project of great interest. And EPRI really did very well in that role. And I will say, in fairness, I think that was one of the casualties of restructuring and deregulation. And I think kind of an obvious one, again, from just a pure sort of economics and business law standpoint. "Oh, if you're going to take something that was a regulated monopoly and create competition, oh, sorry, you can't have all these competitive entities jointly funding an umbrella research organization." And it took a little while. I'm kind of surprised that didn't happen instantly. But over time, in fairness, I think that's basically what happened to EPRI. They can play, I mean, almost like a business coordination role. But they play a much smaller research role than they did three decades ago.

Julie Cohn (01:01:07):

Did they have their own research teams at that time?

Christopher DeMarco (01:01:10):

They did have a staff of very capable technical people. Rarely would they directly conduct the research, but they had knowledgeable people to manage as program directors of this research.

Julie Cohn (01:01:23):

They could understand.

Christopher DeMarco (01:01:24):

Exactly. Exactly.

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Daniel Molzahn (01:01:56):

So, one other question around this. We're going back to an earlier point in the discussion. How much were you sort of, especially in the voltage stability work, but I guess as a general question, were you kind of taking existing control theory ideas, that the broader controls community had developed and established, and applying them in this context versus developing new methods for power system applications that maybe then fed back into the broader control community? Because I feel like you're sort of at this intersection between those two communities.

Christopher DeMarco (01:02:31):

I'd like to think there was back and forth in both directions. You know, there were certainly range of ideas. Not exclusively in control. I would say some of it was more on the theoretical side of circuits and systems. Some of the early voltage stability ideas and sort of inspirations that I took were from ideas in circuit theory that Leon Chua had looked at. This idea that when you get a, again, a model, perhaps an imperfect one, but one that seems to do well, predicting behavior over some range that mixes differential equations and algebraic constraints, from a pure mathematical standpoint, it's very important to point out, with certain fairly mild assumptions, a set of ordinary differential equations satisfies existence and uniqueness. You know, give me any initial condition, I can trace a solution out to time infinity. Give me a set of differential equations with algebraic constraints on them,

Christopher DeMarco (01:03:44):

in essence, you are moving on a manifold, moving on a surface. You're no longer guaranteed that existence of solution for all time. You can have a solution that exists perfectly well and behaves for a finite period of time, but encounters a finite ending point, beyond which solution can no longer continue. Nature probably doesn't do that. We haven't been around long enough to know for certain, but at least thus far, nature doesn't seem to do that. So it probably says something else needs to be added to your model. And when we took power system stability models and brought in what, to best of the state of the art at that time seemed like perfectly reasonable models of voltage magnitude and reactive power behavior, we brought algebraic constraints onto the differential equations. We created this surface, this manifold on which the dynamics had to move.

Christopher DeMarco ([01:04:40](#)):

And oh yeah, sure enough, you could hit a point where solutions in that model couldn't be continued. And again, the circuits, people had seen this, I want to give us some credit in the power system side, on the circuit side, in much lower dimensional phenomenon. Often just in a single dimension, certain forms of oscillators, which showed this behavior. And then you would introduce a perturbation to that original model with some physical basis to say, oh yeah, here's a little parasitic element that you may have overlooked, that introduces an additional piece of behavior. And suddenly now you can get this relaxation oscillator effect, where you have something that moves smoothly. Seems normal circuit dynamics. Hits a point where it seems like you can't go any further. Oh, if you then bring in a little things like, oh, sorry, build a circuit with conducting wires, and there is inductance in that wire, that you may have chosen to overlook, but if you include it suddenly now you've got this perturbation effect of very high speed, that jumps you to a whole other part of the surface.

Christopher DeMarco ([01:05:48](#)):

You move along that part, you jump and you've got an oscillator—in one or two dimensions. In the power grid, much higher dimensional problem. But conceptually the same thing. And in a sense, again, coming back to this idea of looking for sort of qualitative features, many of these descriptions of voltage collapse, from the few incidents that actually occurred, would describe a system seemingly drifting along. Yeah, getting into trouble, moving to lower voltages, but moving smoothly in a way that seemed understandable and controllable, and then suddenly hitting a point and very rapidly dropping off the edge. And that seemed to fit this sort of impasse point and then additional parasitic dynamics that you might normally be able to overlook. But when you hit that point, they would come to dominate and describe this rapid decay towards, then, failure, circuit breakers open, all kinds of things happen.

Christopher DeMarco ([01:06:46](#)):

But so that kind of crossover between circuits and systems and power systems was, I think, quite active through the '80s certainly. You know, a number of other of my contemporaries often published stuff in circuits and systems and power systems. That avenue, with time, seemed to change as well. I think, as the power grid devoted so much interest to kind of the economic side, sometimes still with dynamics and optimization, but I think the folks on the circuit side said, "you're getting a long way from the physics of circuits. You don't belong here anymore."

Daniel Molzahn (01:07:31):

So were there circuits people that were looking at the power grid, or people coming out of primarily circuits background that looked at power grid problems at the time? Or was it mostly power grid people publishing in circuits?

Christopher DeMarco (01:07:42):

I think it went both ways for a while.

Julie Cohn (01:07:48):

Would any of you like to jump in with a question at this point?

Manish Singh (01:07:52):

I had a question. So today at the landscape of research in power systems, we have a lot of interdisciplinary people from control signal processing, operations research, and so on. And one typical point of discontent within the community there is a choice of models. So more control theoretic people would like analytical claims and would go for simpler models. And the simulation-based community would want to model all systems to make sure that it's as precise as can be, so how was the interdisciplinary landscape back then? Were models a fighting issue or were there better ways of coming to the same table?

Christopher DeMarco (01:08:29):

There were undoubtedly still disputes. I think that's inherent when different communities with different ways of looking at things come together. And I think it can be fruitful as well. Not all disputes are a bad thing. But I think I will say that, just inevitably with the growth of the power of computational tools, and, shall we say, a more purely algorithmic viewpoint on making predictions, I think that side has gained greater weight and maybe has a stronger case to make. I'm enjoying a book right now that is perhaps causing me to reach beyond my area of expertise, *When Einstein Walked With Gödel*, speaking about some of the disputes in physics. There's a chapter that sticks in my mind, the author entitles "Is Beauty Truth?"

Christopher DeMarco (01:09:37):

And I think those of us on the analytic model side would like to believe beauty is truth. That a model that is more compact, more elegant, somehow must fundamentally be a better representation of reality. And I think conversely– I think you've, for a long time, seen it very strongly, probably, on the medical community side–I find myself bristling at this, and I know I shouldn't—but even in the popular press over the last few years, you've heard of what I would call a "glorification" of evidence-based methods. But I think what they really mean, if I come right down to it, is “we're going to take a bunch of observations and construct a statistical model that fits those observations.” We're basically making empirical estimations of probability distributions. And that can be a very powerful method. But don't throw away all your priors.

Christopher DeMarco (01:10:35):

Don't throw away all your information about how the world works, and just construct from scratch based on your observations, unless you really don't know anything about the world. And I'd like to think that there can be a meeting of these two sides. And I think there is, I don't want to pretend that there aren't lots of folks with this insight. I mean, anybody doing a good job in estimation theory is taking a Bayesian approach, using prior knowledge, whether it's in the form of mathematical model or other representations of the priors. And adaptively updating that with the observations, with the evidence. But it does get unfortunate when the two sides get entrenched, and it has to be all of one or all of the other. And I do think a lot of the recent past, and in public policy, I understand how this came about, but I think there has been a tendency to wrong-headedly, say, “following the science” is exclusively the evidence-based approach.

Christopher DeMarco (01:11:38):

And if that throws away the priors, particularly in a field like power, where there are a lot of constraints put just by the basic physics–. You don't move hundreds of megawatts and gigawatts without being very constrained by the physics of how that process operates. That's not to say that there isn't lots of complexity brought in by, again, perhaps even the particular algorithms in a particular controller, and you've deployed hundreds of thousands or millions of these things, and that may need an evidence-based approach because you may not have physics underlying that behavior. But a careful blending of the two, I would like to think, is where the field needs to go. And, and I want to believe lots of folks are doing that. But it's not to say that each camp can get a little entrenched at times.

Manish Singh (01:12:32):

Did you like taking your work to different venues? Like were you attending like control theory conferences and seminars and workshops and then power systems? Or was it more united back then—one venue was serving the purpose?

Christopher DeMarco (01:12:44):

No, no. I think actually there did tend to be a lot of venues. So across, coming back to my earlier comments, the ISCAS, the International Symposium on Circuits and Systems was, in the '80s and '90s, a venue for some of the more theoretical work in power. Particularly if it was sort of dynamics of the network itself. I think the control community, there was definite interest. And at times problems like feedback-linearization in control of generators and things would have outlets in the control community. And then things that got closer to application would see presentation at the general meeting.

Manish Singh (01:13:35):

Thank you.

Julie Cohn (01:13:37):

For the purpose of the record, what were the organizations that the control community participated in?

Christopher DeMarco (01:13:43):

I think a significant venue for presentation of results was the Conference on Decision and Control, which is, I think, jointly sponsored by IEEE and perhaps ASME or some of the mechanical-engineering-oriented societies and even chemical engineering.

Julie Cohn (01:14:03):

And the—?

Christopher DeMarco (01:14:07):

The other venues I think are exclusively IEEE. So, the general meeting of the IEE Power and Energy Society. And then the International Symposium on Circuits and Systems is the IEEE Circuits and Systems Society.

Julie Cohn (01:14:22):

Okay. Thank you. So, do you see the validation process now moving toward that intersection you were describing a moment ago between observation and—?

Christopher DeMarco (01:14:34):

I hope so, I hope so. I'm not completely confident that it's happening, but I believe so. And I see, certainly there are lots of opportunities for that to happen.

Julie Cohn (01:14:46):

Any other questions? Okay, go ahead.

Christopher DeMarco (01:14:52):

I can't resist. I do remember a comment that one of my classmates made, who many of you may know, Steven Boyd. But I think in fairness, he was describing something that we all were guilty of. But I think Steven once said that he most hated the folks who would pretend to be mathematicians when speaking to the engineers and pretend to be engineers when speaking to the mathematicians.

Christopher DeMarco (01:15:23):

But I think he was recognizing behavior we were all guilty of at times

Daniel Molzahn (01:15:27):

Maybe one other question along those lines of these different communities. So, if I'm understanding correctly that in terms of the timing you were working with Felix Wu and Art Bergen at Berkeley.

Christopher DeMarco (01:15:41):

Yep.

Christopher DeMarco (01:15:42):

That was part of the systems engineering for control effort? Is that right?

Christopher DeMarco (01:15:45):

That's right. So, I think I was catching the tail end of a big funding effort that came out of Department of Energy that Dan is referring to.

Daniel Molzahn (01:15:56):

So, what was that experience like? We've talked with a handful of folks that came out of that sort of effort and it seemed like very impactful at the time. Certainly for a good amount of funding to go into that space.

Christopher DeMarco (01:16:09):

You can decide whether a positive impact or not, but I think we produced a bumper crop of folks going off into academia. So yeah, I can think of a lot of my classmates who went to faculty positions.

Julie Cohn (01:16:22):

Were people not interested in utilities at that time?

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Julie Cohn (01:16:43):

Did any of your classmates go to industry?

Christopher DeMarco (01:16:51):

On the power side? I'm sorry to say, I think I would be hard-pressed to identify one.

Julie Cohn (01:16:57):

I think that's very interesting.

Christopher DeMarco (01:16:59):

In the VLSI field. I mean, we interacted quite a bit with the folks who did circuits work and simulation, oriented towards integrated circuit design. Many more of those folks found opportunities in industry.

Julie Cohn (01:17:12):

So, the industry probably was hiring was more focused on people with bachelor's degrees, master's degrees than doctorates?

Christopher DeMarco (01:17:21):

Realistically, yeah. You know, with some exceptions, I don't want to say there weren't opportunities. And for example, PG&E might've been a potential avenue.

Julie Cohn (01:17:33):

I think the industry was in a different moment at that time. If you have graduate students now who find happy positions where they're continuing their same intellectual work, but in an applied fashion,

Christopher DeMarco (01:17:48):

And I think many are. I think that that avenue is still not huge numbers of positions, not easy, but more open now than it was in the '80s.

Julie Cohn (01:18:00):

The next set of questions really will be forward-looking. So, I wonder if anybody else wants to ask a question backward-looking. If not, I guess, do you see the types of solutions to stability problems that you personally have worked on continuing to have valence as the power grid changes?

Christopher DeMarco (01:18:27):

I would like to think so. I mean, the context is going to change, and I think, as we've alluded to, much of the control effort in the power grid will be—the advertising term many folks like—"democratized." But historically, you could exercise control from still significant large numbers—hundreds, thousands of locations—but in the, shall we say, the sea of the power grid, still a relatively few large points of leverage. Large synchronous machines, the sort of DC power lines I alluded to earlier, their interface points with the AC grid, maybe select large reactive power control devices like static var compensators. So still, shall we say, points of control, nodally connected from a network standpoint. Still relatively few places where you exercise control over a branch, over the flow, although some, but relatively few. Increasingly, the nature of hardware that's being deployed in the grid is making it attractive to move that control down to still large, but relatively smaller devices.

Christopher DeMarco (01:19:56):

So we alluded to batteries earlier. You know, as you install large-scale battery storage anywhere in the grid, that opens an opportunity for control of the flow of power. And if you think about it, if in an electric network that is the power grid, at a point of connection, really your only, shall we say, variables of communication between that point and the outside world of whatever you put there, are voltage and current. And if you prefer, take the product of voltage and current, and then it's power. But that's the only way you communicate physical effects. You know, in theory, other things could happen. There could be thermal effects and things, but those are almost always negligible across any large interface. So you've got all these points in an electrical network, and all I can do is change the net nature of the voltage and current waveforms with control.

Christopher DeMarco (01:20:53):

I'm going to start doing that at a much larger number of points, and it'll be a reasonable architectural question, "How far down does this go?" You know, I alluded to earlier in talking about cybersecurity, oh, if we got every home electric vehicle charger interacting with the grid through an active control, I'll offer at least one personal piece of evidence that the risk of that in the near term may be low. I've got an EV. I bought an EV charger from some outfit, what the heck did they call them themselves? Juicebox. Oh, yes, they were promoting great plans to do all kinds of fancy grid control. "Would you buy in? We will lower your price." I, of course, was paranoid and put on my aluminum hat and said, "no way, you're not controlling my charger." But in fact, they've since gone out of business. They failed as a business venture.

Julie Cohn (01:21:47):

So they're not controlling?

Christopher DeMarco (01:21:48):

They're not controlling anything. Now, I, in truth, I still think eventually that will come, but I think a lot of these things are harder than people give them credit for. And folks who jumped on the bandwagon early found the cost greater than they anticipated, and, more folks put on their aluminum hat than just me and said, "I'd rather have my car charged whenever I want to charge. You know?"

Julie Cohn (01:22:12):

Do you think computing power is keeping pace with the need to be able to do these really enormous calculations to figure out how to control from so many more points?

Christopher DeMarco (01:22:24):

In principle, yes. I think it's less the number of teraflops per dollar you can devote to a problem, than it is good algorithms.

Julie Cohn (01:22:35):

And do you see good algorithms ahead?

Christopher DeMarco (01:22:38):

I think so, yeah. No, I think the ideas are there. But it is again, quote/unquote, this attempt to democratize control brings with it so many organizational issues on top of just the sort of physics of control. So when control was being exercised at a 250-megawatt and up generator plants, only, you knew who was designing that control, who had responsibility for it. And they had all the, not always, but usually had the interactions with the larger-scale grid operators to have a good sense of what was reasonable control action to take it. As a minimum, they had some sort of, here are basic standards. If you at least do this, you'll do no harm. I think as we push this out potentially to millions of individual actors, it may almost become more standardized.

Christopher DeMarco (01:23:42):

It may just become, this manufacturer builds to this standard. But as I know folks dealing with various inverters and other interfaces have seen, those manufacturers tend to be very proprietary about what exactly goes on inside their box. So being able to say all of what the physics of that device is, is often hard. They may say they built to a certain standard, but as I've alluded to earlier there are valid questions of: oh, I built to this standard, but that doesn't really answer everything. Oh, over what bandwidth? Oh yeah, I behave like this. Oh yeah, I validated it with these measurements. Oh, but you validated on a range of zero to four hertz. Oh, what's happening from four to 20 hertz? What's happening from 20 hertz to 200 hertz? You know, it's a much more subtle question than I think some of the end equipment producers necessarily recognized. You know, whether or not that's what put my Juicebox friends out of business, I don't know. But at least that could be the sort of contributor.

Julie Cohn (01:24:53):

Your Juicebox example raises a question about social theoretical ideas that could potentially have a role to play in future modeling of how to make things work. Is that something that has been considered. I mean, in the past you had as you say, a limited number of actors, and they were within identified types of organizations that had a limited number of incentives—like either reliability or energy conservation or something like that. And now we have potentially millions of actors involved whose incentive might be, "I need the car ready because I've got an emergency trip to the hospital." So thoughts about that social overlay?

Christopher DeMarco (01:25:49):

Well, I mean, in a very nuts and bolts sense, just in terms of, of regulatory structure. Historically in the US we drew the line at what constitutes the bulk power system and everything below. Little bit of added history here. At one point, Bernie and I were approached by FERC in a little project to think about how you might redraw that line with a more technological basis. Because in part, the presumption is, "oh, I'm going to draw that line. And anything that's on the bulk power system side can have a major impact across a big geographic footprint and is worthy of worrying about, for things like stability. And anything downstream of that line, oh, that'll be small local effects. So we'll let the distribution companies take care of that." If you believe some of these cybersecurity scenarios of hacking large numbers of small devices, that is not a reasonable assumption, that only the bulk power system can cause problems in the bulk power system.

Christopher DeMarco (01:27:03):

And ultimately, despite our best efforts, yet again, they failed to listen to me. The decision was, "boy, for a regulatory environment, we better keep the definition really simple so everybody understands it." So if it operates at 100,000 kilovolts and up—I'm sorry, 100,000 volts—100 kilovolts and up, it's bulk power system. If it operates at a voltage smaller than that, it's not bulk power system. And that then decides where NERC authority—NERC is now, in essence, for lack of a better term, I'll say sort of a subsidiary of FERC, it inherits FERC's regulatory authority to enforce reliability standards. But for example, NERC has no authority over my Juicebox electric vehicle charger. And I wonder whether—it's hard to imagine the same sort of regulatory bureaucracy that could work for still a manageable number of large corporate entities working all the way down to consumer devices.

Christopher DeMarco (01:28:17):

So some new structure will have to come into being to think about that. You know, it may be as simple as, "oh, we set these standards. Here's how you measure if you meet these standards. And if you meet them, you can sell your device. And if you don't meet them, you can't." But that might not be the most flexible environment in which to operate, but that'll probably be the easy, first way it goes. That's just sort of organizational regulatory structure. I think maybe you allude to a little more than that. You've seen sort of social and cultural questions at the edge of grid operations throughout the years. You know, when a grid entity puts out a sort of public service appeal, "oh, we're under very high load conditions, please be good citizens and try and conserve," you're really relying on certain assumed cultural norms and response.

Christopher DeMarco (01:29:13):

And historically I think the pattern that you've seen, kind of predictable from human nature: initially, you'll get very good response out of that. Keep crying wolf for a week or more, and your rate of response gets worse and worse. So sort of, shall we say social buy-in to recognize this is a system for the broader social good can be important and useful. But I'll come back to my earlier skepticism. Does a competitive environment where the folks actually producing power are based, entirely reasonably, on the rules we've given them, are doing that for maximum profit. Does that inspire the end user to say, "oh, I'm going to do a good deed to make things better for this guy who's making a bunch of money off me"?

Julie Cohn (01:30:05):

Important question. Did you have any—?

Daniel Molzahn (01:30:10):

I don't have any follow ups to that in particular. I have maybe a related question, which is, so since I've been at your retirement party, since you've retired, you've been working on some of these end-use sort of ideas. Can you speak a little bit about what you've been up to the last couple years?

Christopher DeMarco (01:30:30):

So, I joined just a couple of friends who I had done consulting for in a previous startup. They are George Baker, who had previously been a member of the faculty at the business school at Harvard, Jessica Millar, whose dad used to be Associate Dean of Graduate Research here in Madison. And it was through her dad that we met. They had a firm initially that found kind of an interesting niche and, again, weird the way that history comes back to reverberate. But in the earlier days of nuclear power development in the US, some of the concern was you would have these very large power plants who in the early—well, still sort of current days of nuclear design—were very much optimized, operated at fixed output level 24/7.

Christopher DeMarco (01:31:34):

And of course, you'd have patterns of demand that would tend to peak through the day, drop during the night. Oh, could we find ways of leveling that demand curve? So in a number of parts of the country there was—and I think incentivized with various financial schemes—installation of storage heaters, which were basically just big piles of insulated ceramic brick with electric heating elements inside that you could heat electrically during the night and release that heat energy throughout the day. Clock moves forward, deregulation comes in, all that stuff goes out the window, but there's still all these things sitting out there and roughly a couple hundred thousand homes throughout the US. So George and Jessica had a firm that looked at going in and retrofitting those with controllers to then provide frequency regulation services. Not unlike that big field of electric resistors we had outside our wind turbine on Cuttyhunk.

Christopher DeMarco (01:32:44):

I'll digress a little bit. I wish I still had it. In the days of Cuttyhunk, we had a t-shirt made up emblazoned with a wind turbine, some wires, and a huge electric toaster, with an insignia that said, "wind equals energy equals toast." Because it was basically a big toaster we were running out in the field. So here was an example of toasters that could do some good, they could store up heat, and provide useful service to the homeowner. But here again, maybe closer to the Cuttyhunk model, also provide frequency regulation services by fast modulation of the exact amount of current they were drawing. So I helped out in that effort. That firm was called V-Charge and basically, retrofit these things with controllers—predominantly in PJM, a little bit in ISO New England.

Christopher DeMarco (01:33:43):

At that point, it was still an experimental program for little individual loads like this to provide frequency regulation service, but V-Charge served as a consolidator of those services and then would sell frequency regulation service to PJM and ISO New England. They then sold that off to a firm in Great

Britain that was looking at similar ideas. I think has since gone in other directions, as is often the case in startup acquisitions. But they approached me about a follow-up effort, and at that point I decided I would join them in a new firm that we call Gridworks, although we've got lots of competition for that term. There's apparently some educational outfit that uses that term as well. We imagined creating a software project that would integrate these ideas for a range of storage technologies. In truth, discovered that it was a lot easier and more profitable just to provide consulting services to folks looking at doing work like that. So thus far, that's been the nature of our work. But really looking at providing control algorithms to, from the economic side, provide a stack of services that storage can provide with suitable algorithms.

Julie Cohn (01:35:08):

Interesting. Any final questions? Sairaj, would you like to ask your usual closing question?

Sairaj Dhople (01:35:21):

Sure. Chris, this has been a very entertaining conversation. I wonder, if you had to provide some words of wisdom or advice to a future generation of power system potential students or engineers, what would those be?

Christopher DeMarco (01:35:39):

I think we've had a hint of it in some of this earlier discussion. I think we are at an exciting juncture to bring together sort of the physics of analytic models with the—another term I hate, but—big data driven statistical estimation approaches and merge those in a way that could be very fruitful.

Christopher DeMarco (01:35:56):

And I think both the increase in sort of computing power and the algorithms for—again, my prejudice, I know I'm oversimplifying the field, but—I personally, I believe much of big data and indeed even much of AI boils down to creating empirical estimates of probability distributions on a huge scale, over a number of variables that would've been unthinkable in the past. But informing that sort of empirically-based estimation with the priors of analytic models governed by the physics that determine how these, at least on the power system side, how these networks behave, I think is an opportunity for very fruitful work, and, I think a lot of excitement and real benefit in how well these systems [*will*] operate and behave.

Julie Cohn (01:37:04):

Thank you very much. This has been a really interesting interview and we greatly appreciate your time spent with us today.

Christopher DeMarco (01:37:10):

Well, very kind of you. Well, I've enjoyed it as well. Thank you.

*[End of interview]*