Algorithms & Power Systems Architecture:

Using Historical Analysis to Envision a Sustainable Future

Oral History Project

Interviewee: Deepak Divan

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Abstract:

Deepak Divan is the John E Pippin Chair Professor and Georgia Research Alliance Eminent Scholar in the Georgia Institute of Technology School of Electrical and Computer Engineering. He also serves as Director of the Georgia Tech Center for Distributed Energy. He has founded numerous companies and holds many honors in the industry. During this interview, Dr. Divan discusses his background in India. He describes studying analog electronics and audio amplifiers, working with thyristors in a master's program at Calgary, then returning to North America to complete a Ph.D. after running his own company in India for several years. He describes taking a position at the University of Wisconsin in a program called Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC). He also describes collaboration with Jay Baliga who had invented the Insulated Gate Bipolar Transistor.

Dr. Divan explains the difference between hard switching and soft switching and how each type of device affects power loss. He describes the start of his company, Soft Switching Technologies, and his collaboration with the Electric Power Research Institute (EPRI) and the utility industry. He shares his insight that power quality is not important compared to other challenges on power systems. He

discusses his focus on developing inexpensive devices to collect data, including voltage sags and frequency deviations; noting that with widespread use of his company's monitoring device, he was able to collect detailed frequency deviation data at the time of the 2003 Northeast Blackout. He describes media attention following the blackout. Dr. Divan discusses tight links between academia, his companies, and utilities—via EPRI—that were developed through the process of addressing transmission line overloads. He revisits the work completed with Mukul Chandorkar to develop a control system for microgrids and a ten--year lag after publishing their seminal paper on droop control before industry showed an interest. Dr. Divan discusses his research method and his work with his students to identify flaws as quickly as possible. He later describes collaboration between theoretical control engineers and power electronics engineers. He closes with a lengthy discussion of his concern for the future of power systems. He explains that we are going through a paradigm change, but the people charged with answering questions about the future are experts in the old paradigm. He expresses concern that resources and policies are not directed toward anticipating the new paradigm for the future grid. His worry is that change is happening fast and if we fail to address the paradigm change, we may face failures such as blackouts.

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.

Julie Cohn: This is Julie Cohn, and I will be interviewing Dr. Deepak Divan at Georgia Institute of Technology in Atlanta, Georgia. Sairaj Dhople will be assisting with the interview. Other participants include Rachel Harris and Daniel Molzahn, all of whom may also ask Dr. Divan questions. Dr. Divan, our overall goal for today's interview is to understand your role in developing key algorithms used on the grid and in particular droop control. But first, we'd like to learn more about your background and how you found your way into power systems engineering. So, for just a few minutes, please briefly describe where you grew up and what drew your attention to electric power systems.

Deepak Divan: Well, power systems is questionable, but okay we'll assume that anything with power is power systems for now. No, I mean, it's—I've been around power probably all my life. My dad used to build dams and hydroelectric projects in India, so I've gone through and seen all kinds of—

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Julie Cohn: [00:01] I'm sorry, we had an interruption, but you were describing your father's work on dams.

Deepak Divan: Yeah, so I grew up around hydroelectric projects, big generation plants and how it's built and—so we—that was very, very familiar to me. And so, it was preordained that I'd be an engineer. I told my dad that civil engineering was too obvious; I already knew everything there was to know about it, so I said, "I have to find something that's a little more interesting and difficult." So, I ended up going into electrical. I was the—I came into power completely different way from most people. I came in through analog electronics. I was very interested in audio amplifiers, and I designed and built audio amplifiers when I was in IIT and my first job was with Phillips in India, as part of their acoustic kind of research division, designing [00:02] and building amplifiers.

So that was all power amplifiers. So that was power. I started getting interested in switching regulators around that point in time. But I think that exposure to analog really changed my approach to everything. At that time, people were doing power electronics, really, because they wanted to control the speed of motors. And for them the switches were switches that they had to generate a switching function that would turn the motor, so they didn't really care about the switch. But I came from the analog world, and there was nothing called a switch. It was a device that had characteristics, and had losses, and had this and that, and everything else. So, coming into it, I came in with a very, very different perspective. But that's what led me into power electronics. So, after working for a couple of years after my graduation, I decided to do a master's.

Interestingly enough, as part of my bachelor's project, I built solar cells. [00:03] And then we developed probably one of the earliest MPPT algorithms and had my first journal paper come out of the work that we did out there. So, I was hooked into publications; I was hooked into the research and all the things that we could do with that. And so that's when—that's why I went to Calgary to do my master's and really cut my teeth on power electronics and started really—at that time, only thyristors were there, there was no other devices that were real at that time, so we were working with thyristors. And I think that was also my first introduction to really some of the big kind of stalwarts and then kind of people who shaped this whole area of power electronics—got to meet them.

My advisor was also a very well-known person, Tom Barton, and through him, we got to know a whole bunch of other people. I'll talk about that more maybe later, but [00:04] just to complete the story. So, after doing my master's, I was still hooked with—read a lot of Ayn Rand, when I was in college. And went back to India. I was still very idealistic and started my first company in India, in Pune, and ran that for two and a half years; it was fine. We were going to grow but it wasn't a great time in India to be starting a company. We couldn't get components, there was really no technology elements, there was nothing out there and I didn't want to be selling because I had no competitive advantage, so I could askmy wife reluctantly. She says to come back here so I could do my PhD. And that's when I came back to Calgary, did my PhD out there. It was a pretty rapid PhD because my wife said, "How many years is it going to take?" I said, "Oh shit, I better get this in place quickly." [00:05] And then I started teaching in Edmonton. And that's when Wisconsin came and made me an offer that I couldn't refuse. And they had a very good program, it was called the WEMPEC Program, the Wisconsin Electric Machines and Power Electronics Consortium.

Tom Lipo and Novotny had started that, and they were probably the best kind of consortium in the world at that point in time. There were only five or six companies when I joined. Bob Lorenz was the other person, and he was more a controls guy. And they brought me in to start the power electronics group. And so, there was the four of us, we grew from five companies roughly to 65 by the time I left. So that was, I think, really interesting. I had already had my experience with hands-on entrepreneurship. I understood that part of what it needed to take technology off to market. [00:06] And we were kind of looking at 65 companies and saying, "Here's the great technology, let's get into market!" And they're saying, "No, no, we don't want to disrupt." I said, "Come on, guys. What is the point of doing technology development if you're going to be the gatekeepers and not going to allow new technologies to come to market?" So, I had to do it again. <laugh>

Julie Cohn: So, what was the mission or goal of the consortium?

Deepak Divan: So, the consortium was really built around machines and product drives. So, Wisconsin Electric Machines and Power Electronics Consortium. There was a need—I think it was the first university-industry consortium—and it was filling a really important need as industry was grappling with new, fast-moving technologies, they didn't quite know how to integrate that into the product lines. They were struggling with where to get students [00:07] who were well-trained in these areas. And this was not just a national phenomenon, it was a global phenomenon. This was still when most countries were starting their big programs, research programs, and we had people from virtually every country that were out there as postdocs, as research professors, and as everything else, so it grew to be a big community—a big family of people. And I think I learned a lot about what to do and what not to do. So—

Julie Cohn: What were the years that this was taking place?

Deepak Divan: So, I joined Wisconsin in 1985, and I stayed on the faculty till '95 and then started my first company in North America. So, this was Soft Switching technologies in '95, and ran that there to 2004, then moved here at that point in time. That was the period over which—and it was a learning curve for everybody, this was very unusual to [00:08] have faculty jump in as start these ventures.

Julie Cohn: So, what was going on in the power industry at that time? Was there a problem you saw or a problem that industry professionals brought to you that you thought your company could solve, or were you working in other sectors?

Deepak Divan: That's a great question. So, the consortium itself was initially focused purely on drives: motor drives and motors. I came in with a much bigger interest. I really was interested in the intersection of the grid and other systems. In my PhD itself, I think we—I wrote the early papers on the interaction of converters into grid in terms of harmonics, how could you design converters to minimize power factor harmonics, and things like that. So, I already had a very strong interest in that space, but there was no demand for anything [00:09] at that time; utilities were not looking at any control. There was work going on at SMES conducting magnetic energy storage. Jim Skiles was there, and he was Ned Mohan's supervisor.

It was a completely flawed concept from day one. <laugh> Sorry to say. <laugh> Football field size—like super compact it's not. And you get two seconds of energy storage with that, something like that. <laugh> So, that wasn't going to go anywhere, but it was a lot of work that was being done. Around the same time—so you remember, I mentioned that I came in with this analog background, and at that time, we were using silicon devices—so we made the transition from thyristors to silicon transistors, which they always had transistors, they were terrible. [00:10] We had—in the analog world, you used to transistors with a gain of 400; well, in power, we had gain of five.

And so that was not a very, very good transistor; the gate driver was more complicated than the converter itself, so this was not going very far, very well, until the Japanese jumped into the fray. And they said, Let's make things really bad, let’s take a transistor—which has a small drop—and make it a Darlington out of it, triple Darlington, so that you only need two amps to drive it, rather than 30 amps to drive it. And it's a bad idea because you end up having a high voltage, so nobody in the USA was looking at that and saying, There's not a reasonable solution. But what the Japanese did was they turned that into a module that could easily be used: it took all the engineering out of it.

As long as it could manage the thyristor. And suddenly that power electronics started exploding because [00:11] we took the thyristor out of it, we took the commutation circuits out it, we took all that out of it. So, we were at that point still using bipolar junction transistors, and clearly it was not the best thing, we couldn't switch more than one more and a half kilohertz, and the switching losses were killing us. And that's when we came—I came up with the idea of what we now call soft switching converters. Where we could see that by actively shaping the switching trajectory across the devices, we could get the switching losses out and we could—at that time—raise the switching frequency of the transistors from one kilohertz to about 20, 25 kilohertz. So that was quite a milestone.

And so, again, we started working in that space and then IGBTs came in. Jay Baliga was at GE. He developed the IGBT—couldn't find an American manufacturer. <laugh> Finally, the Japanese started manufacturing the IGBT in modules. And that then became—very rapidly turned into—[00:12] I'm lucky to have seen this whole transition from only thyristors all the way out to big devices. And we started to focus on the grid intersection at that point in time. So, I maybe could spend as much time as you want telling <laugh> as many stories as you want; that's not a problem.

Julie Cohn: This is exactly what we want but sometimes it would be helpful when you say an acronym, if you can also explain what the words are.

Deepak Divan: So IGBT is the Insulated Gate Bipolar Transistor. And that device is now very commonly used, and it's now slowly being phased out as well, but for a long time it was really kind of ruled a space. So, anyway, we were talking about the—there's growth in converters, we are applying it into drives. And I'm also interested in UPS systems and trying to apply it in other stationary applications as well. [00:13] And we started working in that space. We were working with a few partners—Best Power was there, Emerson had a big UPS company. We were working with them as well, and so we are working on new solutions for that group, for that space.

Let's see, at that time, we also—I also went and spent a summer in Aachen as a visiting professor. Everybody got intrigued by this soft switching concept and it kind of blew people's imagination. So, we—I got called everywhere to kind of talk about it and the whole concept of hard switching, soft switching all came about after that. And so, we spent time in Aachen and [00:14] we got to visit a number of labs out there and visited Depenbrock lab in Bochum. And he was working for the German railway companies in terms of developing kind of motor controllers. And at that time, motor control was still very difficult.

You can't imagine when riding a Tesla today that that would ever have been a problem, but we couldn't get motors to stabilize, and there would be vibrations, and we needed sensors. We needed all this kind of control, which for locomotives was not so easy to integrate all in. So, they had developed this very interesting technique of direct motor control where which you could do with induction motors and be quite fascinated by that, and wanted to kind of see if we could apply it in other spaces. That led to the work, the droop control work that you kind of talk about. [00:15] I had a student, Mukul Chandorkar, and we—you know him, but we—you don't have any other relationship other than the fact you know him, right?

Sairaj Dhople: Outside of that, nothing else.

Deepak Divan: Yeah. Because I know a lot of—I've now worked with him, his student, and his student's students. <laugh>

Julie Cohn: So before we move on to droop control, for the non-technical audience who may listen to or read about this interview, can you explain—pretend it's a class of first-year English majors, undergraduates—the difference between hard switching and soft switching, and why that would matter on a power system?

Deepak Divan: Yeah. No, it's not so much the power system at this point, but it's—if you're building a power converter, a hard switching operation is where you treat the device like an ideal switch, and it switches whenever you want it to switch. [00:16] Tell it to switch it switches. The characteristics of the device—because the physical device is conducting current, it's got charge built up inside it—as you start turning the device off, it takes a finite amount of time as the device is turning off. And during that time, the device is not a switch, it's sustaining both voltage and current as that current is coming down, and that result is that the product of current and voltage [power dissipation] is really lost. So, every time you switch the device on or off, you get a big loss component, which means that if I switch the device more frequently—which is what I want to do to get better transient response and better transponder filter sizes—I end up with a point where I get very high losses. What we were able to do was: by creating an environment where we could turn the device on while capacitors held the voltage at zero, and we could turn the device off while capacitors held the voltage at zero, we found that there was no loss, no switching losses [00:17] on the devices. And so, I could suddenly take that switching frequency up dramatically compared to what any other techniques would've been able to do.

Julie Cohn: So, this was in fact revolutionary?

Deepak Divan: Yeah, I mean, certainly eye of the beholder, but certainly caused a very big, a quantum jump, in performance. It was adopted quickly in the switch mode, power supply area. Not as much —We built big systems; we built for a small submarine, we built a full propulsion system using this out of Wisconsin, things like that, so we did prove the technology. And then I did start Soft Twitching Technologies to commercialize that, but we can talk about why that worked and what didn't work in that space. One other thing that might be of interest for your audiences: there was also the time when EPRI had just been formed—they had been formed essentially after the 1965 Blackout—[00:18] and they said, "You guys don't do any R&D? We got to do something. So do it now!"

Sairaj Dhople: What year was this? EPRI?

Deepak Divan: EPRI would've been about ‘82, I think—or ‘79, ‘80; somewhere around that.

Julie Cohn: I was going to say late ‘70s, early ‘80s.

Deepak Divan: Yeah, yeah.

Julie Cohn: There were some predecessor organizations, but the funding models didn't really work until they started EPRI.

Deepak Divan: That's right. And so, we had one of their project managers, Marek Samotyj. He had come to Wisconsin, and we—again, I presented the soft switching converters. Oh, he got all excited. He said, "We just hired a project manager to lead the power electronics effort and to start a whole new initiative in power electronics at EPRI." And this was Ben Banerjee. So, Ben Banerjee was the point-man for, well, for power electronics, and he's looking for an advisor because nobody knows anything about this new thing called power electronics. <laugh> [00:19] And we need somebody, and you're obviously doing interesting things, so I ended up being the main consultant for his team for 10 years or something. And we ended up putting a lot of the programs in place that are now really shaping EPRI in many ways.

So, for instance, the Power Electronics Application Center was formed in Knoxville, and I was kind of lead consultant, or working with them prior to finding where it was and everything else. And I was also on the committee that interviewed Mike Howard, who went ahead to become CEO. <laugh> And Arshad—now CEO—was a grad student at that time, so this goes back a long way in terms of—but I think what it did was it really started giving us that connectivity with the utility industry in terms of understanding what their needs are. [00:20] And so, we started off with power quality. We did active filters; we installed active filters working with them in the Boston area. We worked with York International to develop a retrofit active filter for their 600- and 900-horsepower chillers and they installed 900, 1,000 of them. So, this is all work that came out of—and my student was Subhashish Bhattacharya at that time, and he's now a professor at NCSU. And I think [he had] the longest PhD program that I know of, nine years, because he kept time taking time off to do all these projects. <laugh> So, he worked on getting this product developed and adopted by York and then he went and worked at Westinghouse for a while and finished, or want to finish it. <laugh> [00:21]

Julie Cohn: I think we may have skipped a transition in your personal life, because you started the company in California and then did—

Deepak Divan: No, not California.

Julie Cohn: Oh, I'm sorry.

Deepak Divan: No, this is still in Wisconsin.

Julie Cohn: In Wisconsin, yeah. And were you still at the University of Wisconsin?

Deepak Divan: So sorry. Yeah, maybe we missed that.

Julie Cohn: Yeah.

Deepak Divan: So, no, but I was still—until this point, we started the company, I was still consulting with EPRI. We were doing all the things, so this was stuff all out there. And we were doing so much of work on resident link converters and kept talking to the big guys and saying, This is interesting; oh, it's five percent too expensive, we don't—. So, I learned that the R&D managers of big companies are really the gatekeepers of technology. Because it disrupts them, and that's not what they want; they don't want to be disrupted. So that's why I said, "Well I'm going to start it, and we'll see where that goes." And that's kind of—[00:22] I ended up having—six of my students came and joined me.

Julie Cohn: Oh, wow.

Deepak Divan: And I think entrepreneurship gets everybody fired up. <laugh> It's very, very interesting and exciting.

Sairaj Dhople: So, it seems to me that you had two distinct types of agencies approach you with problems. One were—let's say vendors that were—

Deepak Divan: Companies, yeah.

Sairaj Dhople: yeah, right—building specific end-use applications, and then the other one was, let's say, through EPRI, like utility-scale applications.

Deepak Divan: Absolutely.

Sairaj Dhople: And somehow, would you say like, the advances in semiconductor technologies were just very, like fortuitously—all of this happened at the same time somehow? Like, was it just by chance, or—?

Deepak Divan: I think there was a—as the devices were improving, the markets were exploding, so the interest was increasing. So, it was—it's all kind of—all happened with all symbiotic. And that learning curve has not [00:23] changed—it's going on now. It's still going on. This is really the fascinating thing about this whole thing. And you know: what caused this to happen? I think if this hadn't happened, something else would've happened. But the pressure was high. Somebody needed to come up with a device that did not have a gain of five. <laugh> It was a MOS input device that did not have really bad reverse bias safe operating area, so that thing would break down all the time. And we needed devices that would be robust, could survive a short circuit; all the stuff had to be done.

But it was clear from the application perspective where people were using the devices as to what was failing. And so that feedback was going to the device manufacturers, and it was just a matter of time before they started coming out—and IGBTs [00:24] went through eight generations in the last 15 years. So, they kept consistently getting finely tuned—better, better, better. So that process was going on. But yes, I did work with utilities quite a bit. The model at EPRI was fundamentally different at that point in time. And EPRI was more of a conduit for research; they were really managers. And so, we got to do a lot of the research. I joke with Mark McGranaghan—and he's a good friend—that, "The first 10 years you gave us money, now we are giving you money. It's not a good model." <laugh> But we had very good contact with utilities, and because I was a consultant for him, I was always around. They had good confidence [in us], and so we got really good at kind of a dialogue going in, and I got a feeling for where the problems were. The most important thing I discovered through all this process was that power quality is not important.

Sairaj Dhople: [00:25] It's not important?

Deepak Divan: Not at all! A big company like Southern Company has two people focused on power quality, and their fundamental job is to make sure that their squeaking customer is quiet, <laugh> because there's nothing they can do. This is not a problem that can easily be solved. But you cannot say, "I don't care about power quality," so everybody says, "I care about power quality." And we learned that the hard way in that first company we started, because they said, Power quality is a problem, so we'll solve it, we can build active filters, we can do this. And at the end of the day, yes, we'll do one and we'll put a pilot. We worked for Southern, we actually built —. They said, "Oh, there's a customer here. It's a big problem." So, we did—we built, brought it here. They said, "How many more?" We said, "What do you mean how many more?" <laugh> The one customer, he had a problem. We fix it, I'm done now. <laugh> I said, "No, you don't build a company like that." Because from a company perspective, you [00:26] need to have a scalable business model. I can't hire 10 engineers and put them to work to solve one customer's problem, and then after that I have nothing: now what do I do with these guys? Fire them? So, this problem is not understood by the utility industry at all, and still not understood by them.

Julie Cohn: And when you say *power quality*, what precisely do you mean for non-technical?

Deepak Divan: So, power quality means a lot of things. It means: is the voltage within bounds? Is it out of bounds? That's power quality. Are there harmonics in the system? Are there transients on the system? Are there voltage surges on the systems? Spikes on the system? Sags on the system? These are all manifestations of power quality. Utilities will keep telling you frequency is important.

Julie Cohn: And this would matter a lot to a customer, not the home cook in her kitchen with her electric stove or his electric stove, but to somebody say manufacturing a textile, a very high quality—

Deepak Divan: [00:27] So this is really interesting story—

Julie Cohn: or a computer. Go ahead.

Deepak Divan: This is a really interesting story—good learnings out here. So, we were doing soft switching inverters, and we were getting really good success. We built some really fine—at that time, in '95, we were doing 70 kilohertz switching with IGBTs and giving probably the highest performance inverters. But then I learned a very important lesson. As a naïve entrepreneur, I said, "Well, I got a better inverter. It's a better mousetrap." I should be able to go to somebody who's selling inverters, "I got a better mousetrap." And no, it doesn't work that way because they already have a mousetrap, and they've invested a billion dollars to make that mousetrap. And what are they going to say? <inaudible>

So that was not a [00:28] workable model. The savings could not—who gets the savings? That is the problem. So, I learned that we had to go to the customer who gets the savings because then you can share in that saving, and you make some, and he makes some, and then it's a good situation, which means you're disrupting other people. But that's fine—I'm an entrepreneur; I don't care about disrupting other people. <laugh> It's part of part of life, so that's okay. So, we decided to focus on exactly this thing. We said, Obviously, all the big manufacturers are saying, power quality, so what is that major power quality thing that they should worry about—harmonics? We could see that nobody cared about harmonics. There were a few things that you could kind of pinpoint.

Those were really not—you needed something that was repeatable, that created an ongoing disturbance they could see, and that would create a business opportunity. And that just was not coming from these regular things. [00:29] At that time, EPRI released what they called the “Distribution Power Quality study,” DPQ study—sort of [around] ’94, ’95, I think it was. And that characterized a whole bunch of—so they had these really expensive $8,000 monitors that they deployed everywhere and collected data. And it became very clear that voltage sags were really the fundamental problem. And when we sat down and thought about, it became very clear: if you get a fault on the system anywhere, you get a small area where this fault occurs and it gets cleared. So, that area sees an outage, but everybody for 30 miles around sees the voltage sag. So, on a statistical basis, you're going to see a lot of voltage sags. So, we said, Okay, fine. So, then we went and talked to companies, and they said, Oh yeah, it's a big problem, so get an engineer to fix it. [00:30] <laugh>

So [we said], What—why don't—you have problem? He says, "No, no, no. Get the engineer to fix it.” Because most companies did not have enough of a problem; they could get utility to fix it, happily, but they weren't going to spend money on it. So, we talked to people like GM and said, Here, you know can both—. He said, “Oh, we don't have any voltage sags.” I said, "Well, how about some monitoring?" He said, "I don't want to spend 8,000 bucks buying a monitor." So, I said, "Now what do I do?" I mean, we could see we had a solution that would be able to cure voltage sags. So, we said, We need to find a really low-cost monitoring system for them that I can deploy anywhere in the country. Remember, this is ’99, ’98, ’99—nothing is there at that point in time, and monitors were $8,000. So, I told my guys, I said, “Let’s find a cheap DSP.” We took the Motorola phone, DSP—which was over five bucks—and we built the power monitors system, and it was internet based [00:31] at that time. It would dial-out—very smart—dial-out, based on—and then we could build it for a hundred bucks.

And it wasn't because we were trying to make money selling them, but because we wanted the intelligence coming back to us. So, we went to GM and said, I have this big monitor. He said, "No, we don't have any problems." So, I said, “How about if we give it to you for free?” He said, “Yeah, I have 70 plants. I want two for each plant.” <laugh> So, we got 140 monitors, and then all of a sudden the data started pouring in. And now you could start seeing the voltage sags. We would contact the utility and say, "What happened at 3:45 in the afternoon?" "How do you know?" <laugh> But what it did was it started giving us the data and then we had a line of voltage [00:32] sags.

So that was the first real intersection of the grid and the industrial customer that was really based on grid operating that we got involved in. And we had a non-battery solution where we could fix the voltage, and we sized all the way up to four megawatts and 25 kilowatts—even small DySC control—all the way up to that. And EPRI was very instrumental in testing it and everything else. And that was a good experience for us, and it started getting deep into the utility world at that point in time. And then the 2003 Blackout happened, right? What am I missing? Am I missing any other stories? <laugh>

Sairaj Dhople: We'll go back to droop control at some point.

Julie Cohn: Yes. <laugh>

Sairaj Dhople: But I don't want to interrupt your—

Julie Cohn: Yeah, I mean, the flow of your stories is terrific. So, if you want to carry on, feel free, or we can ask you about droop control.

Deepak Divan: Yeah, either way is fine. We can just finish this story and [00:33] then we can go back and revisit some of it, because by then we'll come back to more utility-oriented stuff, and then we can go back in time and then come back. So, I think we ended up having these monitors deployed all over. We had Ionics, Lucent, Craft, BMW, Ford, and GM; everybody was a customer. To anybody with big manufacturing plants we could kind of show this could be a viable solution. And then in 2003, the blackout happened. I was coming back from Portland, getting on the plane and my guy calls me and says, "Something is happening on all these monitors that are coming, <laugh> what is happening?" And I said, "Well—"

Sairaj Dhople: How many did you have at the time?

Deepak Divan: In the Northeast, we had about 250 monitors. And I said, "Well, I'm getting on a plane right now, just get the data and when I come in, we'll take a look at it." So [00:34] I reached Madison, started looking at the data, and it was just a whole bunch of monitors doing things that we couldn't—they were seeing outages, but we didn't know what was happening. So, I said, "Okay, let's just do one thing." We were measuring dynamic frequency on these low-cost monitors. I said, "Who needs it if frequency doesn't vary? But it doesn't cost us anything; let's measure it." And we were doing this time interval conversion measurement.

So, every cycle we've measured the period and flip that, and we'd have a frequency. So, every—and so I said, "Let's just take all the monitors that we have and just put them on and chart frequency." And it was amazing because all the eigenfrequencies of the system just popped out. And you could see which parts separated out and which went down. We saw New York City go down to almost 48 hertz [00:35] before the whole thing tripped. <laugh>

Sairaj Dhople: Wow.

Deepak Divan: It was astounding, and what to do with this? So, I just put it up on our website. <laugh> Yeah. <laugh> 4:00 in the morning, I get a phone call. "This is CBS Evening News, we spent the last two hours on your website." We started talking to them. I was supposed to go to Atlanta; we didn't go. We spent two days with every TV network in the world, parked in our camp, in our parking lot outside. And it was funny because—I can see this guy, if I remember—he's trying to put words in my mouth and say, "Oh, you know what I mean? Was this, what? a terrorist event? Was it—." [I responded], "No, I have no evidence to say." And he kept trying to do that. Then what they did was say—at that time, when we were publishing this data, because we wanted to publicize [00:36] the fact that sags were occurring, but we didn't want to say who the customer was—so, at that time, we said, Here's a zip code, and here's the sag data and your time. Well, we didn't know, but turns out that the entire GM plant was a zip code. <laugh> So, the next news going on was: the blackout started at the GM plant. <laugh>

Julie Cohn: Oh, no. Which wasn't really the case. <laugh>

Deepak Divan: Was not the case at all.

Julie Cohn: So did you intersect with or interact with NERC at all to—

Deepak Divan: No, we did a lot with DOE at that time.

Julie Cohn: Okay.

Deepak Divan: So, it was Jimmy Glotfelty. He was the—

Julie Cohn: Oh, because NERC wasn't yet the regulator.

Deepak Divan: Yeah, right. So, Jimmy Glotfelty, Allison Silverstein, a whole bunch of people, Gil Bindewald. So, I—we—because we had data. And then that's kind of where we [00:37] spent a lot of time with them. And, in fact, you could go look at the task force report; that chart is the only one that's there. <laugh> And our companies are mentioned by name. I said, "This is cool." <laugh>

Sairaj Dhople: So just to be clear, these deployments were part of your entrepreneurial venture?

Deepak Divan: Yeah, yeah.

Sairaj Dhople: And the name of the company was?

Deepak Divan: Soft Switching Technologies.

Julie Cohn: But you were still at University of Wisconsin?

Deepak Divan: No.

Julie Cohn: Oh, you had left by then?

Deepak Divan: Oh, yeah—left by then. I was in Madison, where we were running Soft Switching Technology.

Julie Cohn: Were you interacting with the academy at all during those years, or were you just focused on business and—

Deepak Divan: Oh, with the UW?

Julie Cohn: With UW or any other academic—

Deepak Divan: Oh yeah. I mean, I was still kind of supervising grad students and interacting with them. So many of us are still part of the family.

Julie Cohn: Did any of their research direction—I mean, if you were supervising the students, [00:38] were there intersections between what you were doing as an entrepreneur and what the university faculty—

Deepak Divan: Everything that we did at Soft Switching came out of our work at the university.

Julie Cohn: Okay.

Deepak Divan: Right. So that was—

Julie Cohn: So, there was always a tight link?

Deepak Divan: Very tight link between the two. And the last thing that kind of links back to this—which is another kind of link bringing me closer and closer to the utility world—is that it became very clear that the thing that really triggered that was the lines were getting overloaded. They had failed sensors and a whole bunch of cascading reasons. But it was clear that if you could direct the power flow away from that line, a lot could have been saved. That's a big phase shifting transformer and big fax device, and fax device have their own problems. UPFCs are a big problem. There's a reason why only three have been ever built in the world—[00:39] that's a different discussion—but I'm saying, “How can we have a very simple solution for this problem?” And because clearly to cut the wire and put something that’s big, so driving from Chicago to Madison and seeing all these birds sitting on—I said, “That's what we need to do.” <laugh> So that was the beginning of Smart Wires. And at that time, we had—Terry Boston was at TVA. He was the VP out there, and Dale Bradshaw. And they got really excited by this. And we went to Imre Gyuk in DOE and he was kind of running the program and he gave us seed funding to go build the first prototype. And by then, I was hooked on kind of grid-related things and Soft Switching. We had new [00:40] investors come in, and I wasn't getting along with the board at that time. I said, "You guys run this, the products; I still got EPRI." It eventually got sold at Rockwell and they still have the site directors. They still have the i-Grid system. This was i-Grid—i-Grid and i-Sense, well before iPhone ever came out.

Julie Cohn: So, let's circle back. I don't want to keep you too much longer.

Deepak Divan: No, that's all right.

Julie Cohn: So, let's circle back to the droop control topic and do you want to frame that?

Sairaj Dhople: So, I think—if I get this correctly—you were looking at some applications in Europe related to transportation?

Deepak Divan: In motor drives. We were looking in motor drives. And we were looking for sensorless control of motor drives. There was one group out of Japan, Isao Takahashi. And Depenbrock. Not these two, but I mean, these two [00:41] in my mind kind of set the bar in terms of—

Sairaj Dhople: What was the other one you said?

Deepak Divan: Isao Takahashi and Depenbrock. Depenbrock was out of Germany, and Takahashi was out of Japan. So, we started looking at that whole way of controlling the motor and this was really flux control, and it was a state of flux control. So, it was involved in integration of the voltage, and you could see that it was really—the torque was generated by controlling the angle between the flux and the current, on both which were continuous. And so that kind of triggered a thought and I said, "Can we use that essentially to control inverters that are not—." Because ultimately, at the end of the grid is a motor. <laugh> Somewhere back there, there's a few synchronous machines or motors that can control the motor. I can control my power flow against that. [00:42] So, that kind of was the beginning of our thinking about that. But we didn't have this use case, yet, of a lot of DERs being connected, because the price points were simply not there at that point in time.

Julie Cohn: Distributed energy resources?

Deepak Divan: Distributed energy resources.

Julie Cohn: DERs?

Deepak Divan: DERs. So, the question at that point in time was: What was the right application? We were working a lot with UPSs as I mentioned, and we could see that you might have an office building with 500 UPSs. And none of them were talking to each other or supporting each other, so we had this idea that: can we build—would now today be called a microgrid, but at that time, we still hadn't developed that word—but can we build a distributed UPS system? But you can't have communication, so can you design them so that they can work without communication? And we knew that droop was [00:43] part of it, but it seemed to us that pure droop frequency, droop control with an inverter setting would be very angry in terms of control.

It was really angle that was controlling everything. And frequency was differential of that, [and it] seemed to us that that would cause trouble in dynamic situations. But when we translated that back to flux control, we said, That is really what we're trying to do, we have a voltage, and we want to be able to push power against it or pull power from it. And it really is that. But there was no equivalent of flux in the grid world. But we said, Yeah, okay. So, we integrated that voltage flux. <laugh> And that's an integration. So, we thought that would be a lot more stable and so that's what kind of Mukul started on and that really led to that paper. And yes, in the steady state, that's completely equivalent to droop control, but I think [00:44] in transients, it behaves differently and that's kind of what we wanted to do.

Julie Cohn: So, just so I understand, you said that there were these two companies that were doing some work in this—

Deepak Divan: Not company, people. The—

Julie Cohn: Oh, people, individuals? One person in Japan, one in Germany?

Deepak Divan: The other one in Germany.

Julie Cohn: And they were looking at the same topic you were?

Deepak Divan: No, they were looking at motor control.

Julie Cohn: Motor control.

Deepak Divan: They were trying to control large motors.

Julie Cohn: So, were you the only one venturing into this—

Deepak Divan: I don't know of anybody else—I mean, the next paper probably came a long time after that.

Julie Cohn: Okay. Yeah.

Deepak Divan: Because we didn't see citations for that for a long time.

Julie Cohn: So, was this in a situation where you saw an opportunity as opposed to a problem awaiting solution, or was it specifically a real problem that people were encountering?

Deepak Divan: My problem is I've always been way ahead of my time in terms of defining problems, I think that I have never learned how to define my problems based on what other people are doing.[00:45] I've always wanted to go back to more fundamental principles and say, “What is it that needs to be done out here?” To uncover and unpack what other people are doing, I have to be a lot smarter than I am. If I go to fundamentals, it's a lot easier for me to kind of figure out an approach to solving that.

Julie Cohn: So, once you had published that paper, how long was it before there was interest in it in a more widespread way?

Deepak Divan: I would say probably five years after that.

Julie Cohn: So that would be like—what's the timeframe?

Deepak Divan: That's, I think—

Sairaj Dhople: Mid-nineties.

Deepak Divan: That's Lasseter. And what is that, his effort, called, or—

Sairaj Dhople: CERTS?

Deepak Divan: CERTS. All that was coming up in Wisconsin a few years after we had done this work.

Julie Cohn: And was that still primarily an academic setting?

Deepak Divan: There was really no demand for microgrids yet at that time.

Julie Cohn: Yeah, yeah.

Deepak Divan: So, yes, it was—but I think people were getting interested that this had to happen. And it was—[00:46] I hate this; we've done this, we've done big microgrids that force the <inaudible> and things like that and it's never satisfying. It's always complicated, it's never scalable, it's never practical. And if it's not practical, it’s scalable. I'll do it with my nose closed, <laugh> but it's not something I really enjoy doing. <laugh> If I can't scale it, if I can't take it to practical realization, then it's an academic exercise.

Julie Cohn: So, when you were working out the problem, did you envision what we now call a microgrid or were you imagining some of this—

Deepak Divan: Yeah. That's part of the distributed UPS was a microgrid. Today it would be a complete microgrid. And it was—because we were kind of looking at existing office buildings—right from that time, it was always: I don't know when it's grid connected and I don't know when it's not grid connected. And so, the inverters had to figure all that out and keep operating. So, these are some of the same issues we're dealing with now. [00:47]

Julie Cohn: So did anybody ever attempt alternative solutions, or—

Deepak Divan: I'm sure they did.

Julie Cohn: Once you've sort of defined this solution, was that—did that set the standard for others, do you think?

Deepak Divan: I don't even know that; I mean, because I didn't come back to that for a number of years after.

Julie Cohn: Yeah.

Deepak Divan: I mean, I was letting problems drive themselves. In another place where the same thing happened was in this whole area of—we call it dual active bridge converters, which allows you bidirectional power flow on DC-to-DC converters. And we did this project in '89, '88. Mustansir Kheraluwala was my student at that time, and we had—IGBTs were finally available so I could do something with them. And everybody kept saying, High frequency, high this. [00:48] I said, "So, let's see, how about can we build a 50-kilowatt, 50-kilohertz DC-to-DC converter that's a compact building block?" And we talked to NASA, and they got really excited by that and I had to go to NASA Lewis [Field], and I was still on a permanent resident, a green card, so they won't allow me in. <laugh> So, they all came out and listened to the presentation. And that one we literally—because nobody had batteries, so nobody needed bidirectional converters. So that sat—essentially, we did PhDs, and we did a whole bunch of stuff, but then nothing for 10 years, and then it took off like that. Then today, it's—everything is now the electric bridge and I think it's not a very great circuit, but still okay. <laugh>

Julie Cohn: Well, I think that's a really interesting point you're making, and I heard—well, the viewers of this video won't know the reference, but there was discussion in another meeting today [00:49] about something being satisfactory or sufficient as opposed to perfect. Do you have any further thoughts? You're describing a situation where you came up with a solution that was sufficient.

Deepak Divan: No. It was sufficient and it was doing something uniquely, and when the need arose it happened. I remember Hiro Akagi, a good friend of mine, he's a very well-regarded professor in Japan. He came to me in 2005, 2006 timeframe, and says—he was talking about dual active bridge—“Great, and finally, your patent is expired; now I can use it." <laugh> So, we have a lot of that also happening at the same time. Yeah. But—

Sairaj Dhople: Sorry, so I have an unrelated question. It seems to me that you were able to pursue things and then keep them on the side and then look at other [00:50] things. I just wonder, like: did you get feedback from the community that suggested that a bunch of other people are looking at this, and did that ever prompt you to go back and revisit some of the things that you did? Because it seems to me that today with IEEE Xplore and Google Scholar, like we get—we are inundated with that feedback from the community, which maybe keeps us tied to problems because there is interest in them, but it seems to me that you did not do that. Like, you did a few things, you kept them on the side, you kept—maybe came back with that?

Deepak Divan: No, it’s not—I don't think it's even that. All the things I did were driven by a market need. I could see there was a real need for that. I was also equally comfortable. I could define fundamentally that there's the market need and I could develop a solution, but if there was no traction, [00:51] then I wouldn't go and spend another five years developing further refinements on it necessarily because we solved—the fundamental problem got solved. Now, we keep refining it forever, but, I mean, we had solved a fundamental problem and we'd go back to it. So, my charge to my students always is: I want to find the fatal flaw as quickly as possible. So, we are poking at things from the beginning, from every direction where we can, because if it's not going to work, I don't want to find that out after three years. I want to find that out now so I can stop working on it, or at least I can put it on the shelf. So that is the kind of thing that drives that. So, we solved the distributed UPS problem. And I said, "Great, we have a really good thesis, we've got some really good work done. Now, can I use it?” There was no place to use it at that point in time.

Sairaj Dhople: So academic aspirations or academic metrics, would you say were not really your driving force? [00:52]

Deepak Divan: They've never been my driving force. I'm an unfortunate academic. <laugh> Never been my driving force.

Sairaj Dhople: I think you don't have a Google Scholar profile I've checked.

Deepak Divan: I didn't even know I could have one. <laugh>

Julie Cohn: So, we're closing in at the—towards the end of probably the amount of time we should spend this evening. I'm going to see if Daniel or Rachel had any questions they want to ask you.

Dan Molzahn: Yeah, I did have one question for you.

Deepak Divan: Sure.

Dan Molzahn: So Sairaj and I spent some—we're at the CDC IEEE Control Decision Conference a month or so ago and David Hill gave this really nice lecture on the role of the controls community in the past of power systems and looking forward into the future—sort of a call to arms for the controls community. And so, I was curious, was there much interaction between sort of the control theoretic automatic control sort of folks and the power electronics people when you were working on [00:53] these ideas? I just wanted—interesting that the droop control ideas came out of flux control of motors. It makes sense when you describe it, but I would've thought you talked with someone like David. Was there an interaction?

Deepak Divan: There was interaction. We had people from the controls community at UW Madison as well. But I think I was probably interacting a lot more with Bob Lorenz, who was also a control guy, but much more hands-on—much more, and so that was more of the flavor that I had. But again, I think this field has come a very, very long way; it's amazing. And I think we are just on the cusp of major transformation. And I worry a lot, and you've kind of seen me reflect that back in UNIFI as well. We didn't really talk [00:54] about some of the algorithms and everything else. And what worries me—my biggest worry—is that we are going through a paradigm change. And the problem is: every time we are looking for input and advice, we go to the experts who are all experts in the old paradigm.

How do you anticipate what the questions of the new paradigm are from that group of experts? And everything we see in the last 10, 15 years—every prediction that has been made has been spectacularly wrong. <laugh> And Terry Boston was the first one to acknowledge that. He was CEO of PJM—doesn't get any bigger than that. And he said that in 2010, there wasn't a single utility CEO or Grid operator CEO, who could anticipate that solar or batteries or EVs would be a thing; could not. And they were still focused on 20-year IRPs. But still [00:55] every projection that the IEA made showed that it would grow very, very slowly over 30 years, so the normal processes would take care of it. And it's taken us completely by storm. It completely changes the way—the fact we saw this again; there is the two groups that speak with a different vocabulary: how do you make that come together? And if we don't make it come together, if we don't translate it properly, it's going to be mayhem.

Sairaj Dhople: And by the two groups, just for the audience, power systems and power products?

Deepak Divan: No, it's—yeah, it's power. It's not just power systems and power products; it's really—I'm not talking the technology level. I'm talking at the execution, investment, and kind of operational level. I can hardly think of any utility where people have experience in what power converters actually do, how they do it, [00:56] what the control requirements need to be, what can be done with it, and how to think differently about—I mean, we've had this conversation a lot.

If I have a million inverters, each of them with self-learning adaptive over the air software update—my Tesla is updated, every week is different software running on it—how can you solve that problem mathematically? How can you algorithmically solve that problem? It cannot be done. You can challenge me on that, but I don't think it can be done. <laugh> And therein lies the problem. We are taking the tools we have and applying it to a completely different problem, I think. And therein lies the problem, because now if the first time we stumble, they'll set [00:57] the whole thing back by 20 years.

Julie Cohn: And by stumble you mean a failure like a blackout?

Deepak Divan: Yeah, exactly. So, this is part of what you need to be addressing: is this a paradigm change? I mean, I say you have to learn history because you don't want to repeat yesterday's mistakes, but at the same time, if the paradigm is different, you want to make sure that you don't apply the lessons from the past history to the new future. And then nobody wants to be disrupted. I don't want to be disrupted; <laugh> I don't want utilities to fail, but the problem is—we have an annual symposium out here, and a couple years back, we had one on the intersection of the grid and transportation. So, we talked a lot about charging requirements and this and that and everything else, and there's a disconnect between what the grid can supply and what the charging requirements are. At the [00:58] end of the day, I asked the Tesla guy, "What happens when an irresistible force meets an immoveable object?" <laugh> He says, "We go around it." <laugh> And that, unfortunately or fortunately, is what's happening.

Julie Cohn: Yeah.

Deepak Divan: We're starting to see an enormous deployment of generation at the edge to meet locally, because I can now supply through microgrids. I can supply energy at a cost that is comparable, or lower, than what the grid can supply, so it's going to happen. And you are building all this out, but you can't use it to support local resiliency needs. That's an awful thing. <laugh> So, this is the kind of stuff that we aren't resolving because everybody's kind of proceeding in their own little silos. We had a chart that says everything is going at 60%; it's all [00:59] connected by a grid that's going at 0.25%. <laugh>

So, we put the IRA in place and we're going to spend $2.5 billion on transmission versus $360 billion that we need. Well, if you put the $360 billion and spend it, you get transmission that is utilized extremely poorly because you connect low-capacity factor load to it. And now, what do you do with that? How do you pay for that? So, this is not a problem that is being solved properly, and the answer is not to offer billions of dollars. Because as soon as you offer billions of dollars, [someone will say], "I have a solution that's going to definitely work; <laugh> I want that billion." <laugh> And this is what we see. I was at the White House Electrification Summit, and that's what we saw. They were throwing money at it, left, right, and center. It's all for deployment, whether the solution's right or not doesn't matter; that's a different issue. We don't deploy. <laugh>

Julie Cohn: Do you have [01:00] a vision of the paradigm for the 21st century?

Deepak Divan: I have a vision. One of the things we learned in the National Academies Committee that I was part of, from electrification, the future of the electrical grid, was things are moving too fast in too many different areas, all uncoordinated, all unconnected. And there's a layer of policy on it that is highly regional, and none of it is aligned with reality. And so, what happens is very unpredictable and unknowable. So, the best we could do was kind of look at scenarios. What kind of scenarios can play out? And to start thinking about making investments and developing solutions that were no regret, that would allow you [01:01] to be flexible and adapt. So, to think about this: we treat the linear time and variance system that we've had over the last hundred years as a linear system that is fully knowable and fully controllable, and that's how we treat it.

When you say *smart grid*, it's not really smart. The smart city sits15 minutes away. The system is—now you take them and replace it with intelligent agents that have all this capability and the muscle to do things and everything else, and they all act locally and autonomously based on local input. And to conserve their own cost function. That creates an unknowable kind of architecture out there. So, we have to come up with a different way of analyzing and thinking about this, that really—and I don't want the grid to be disrupted because I don't want my lights to go off. <laugh>

In the ideal world, we would kind of have a transition where you add capability to the grid, but I can't see any of the utilities [01:02] moving at the speed that is needed: that's my worry. And if they can't move with the speed that's needed, the investments in the local distribution are going to keep going on. I had a conversation with one of the major transmission companies, and they're saying, My cost of transmission wire is not going down, but my cost of non-wire alternatives is going way down. So that's more cost-effective for me as a transmission company to put it. That's ridiculous, but this is not being acknowledged anywhere; we’re still doing the same. So that's the problem that we are going to, and if we don't manage to solve it, what's going to happen is these things, they're going to pop up and they're going to break out, and suddenly the underprivileged people are going to be in a world of hurt again.

Julie Cohn: Yep.

Deepak Divan: Equity doesn't come out of this naturally. And so how the hell do we solve that problem?

Julie Cohn: Yeah. That's the next video we'll do. <laugh> We'll discuss that [01:03] problem, which is major. <laugh> Rachel, I didn't know if you had a question.

Rachel Harris: I don't think anything else, but thank you. This was really interesting.

Julie Cohn: Yeah.

Deepak Divan: Thank you.

Julie Cohn: Was there anything else you wanted to offer? I feel that you've really given us a lot of great retrospective.

Deepak Divan: No, I think the only—I think this is a really important topic. That's why I was happy to be a part of it. I think it needs more time, I'm sure. But the thing that you're talking about is that: are we algorithmically approaching it correctly? And I don't think we are. <laugh> And I think the paradigm is changing. And the problem is: if it was a green field, if I could go to Africa and build a grid, I know exactly what to do. But here we want to keep the lights on as we are changing it. Mike Howard, I think, said it really well, he says, “Our job is to completely revamp and change an [01:04] airplane while it's still flying.”

Julie Cohn: Exactly. Without sacrificing the investment professionally.

Deepak Divan: Exactly. Yeah. Exactly. That's the problem. And it's a nontrivial problem.

Julie Cohn: Well, thank you so much for your time. We really appreciate it.

Deepak Divan: No, thank you. That's fine.

Sairaj Dhople: Thank you so much.

[End of Interview]