Algorithms & Power Systems Architecture:

Using Historical Analysis to Envision a Sustainable Future

Oral History Project

Interviewee: Mukul Chandorkar

Interview Date: July 15, 2023

Place: Marriott Hotel, Orlando, Florida

Interviewer(s): Julie Cohn, Sairaj Dhople, Manish Singh

Keywords: Mukul Chandorkar, India Institute of Technology (IIT), ABB Corporate Research, Institute of Electrical and Electronic Engineers (IEEE), Deepak Divan, uninterruptible power supply (UPS), inverter, inverter-based resources (IRB), droop control, power system control, motor drive, renewables, sustainability, electrical engineering.

Abstract:

Mukul Chandorkar, professor in the Department of Electrical Engineering, India Institute of Technology (IIT) in Bombay, discusses his educational and professional experience, training in both India and the United States, and working for ABB Corporate Research in Switzerland before joining the faculty at IIT. He describes his graduate student work in the early 1990s on operating inverters in parallel without synchronization or communication, which led to the droop control method still widely used today. The research process included review of prior work, simulation involving one inverter and a synchronized system, and simulation involving two inverters and a synchronized system. He describes presenting this work at his first professional conference, the Institute of Electrical and Electronic Engineers (IEEE) Industry Application Society meeting in Dearborn, Michigan, in 1991, where it was of great interest. He explains that the uninterruptible power supply (UPS) industry was very interested because this approach helped solve a problem. Dr. Chandorkor names individuals whose prior work in power systems control and whose mentorship influenced his work. He explains the nature of follow-on work to scale the droop control approach up to larger systems. He discusses his work on motor drives in industrial systems, and the parallel approach of modularity in his work. He pinpoints a moment in 1999 when droop control gained widespread interest in the industry. He returns to the topic of modularity related to the proliferation of inverters on the grid and the development of building blocks for power electronics. Dr. Chandorkar reflects on his lifelong interest in taking things apart and putting them together in parallel with his

analytical work. He discusses his interest in sustainability and the opportunity to design and build things, especially power electronics, with end-of-life concerns in mind. He advocates for making sustainability another constraint in the design of power apparatus. He closes by encouraging the next generation of power system engineers to remember the social impact of their work.

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 (00:00:01):

This is Julie Cohn. I am conducting an interview with Mukul Chandorkar on Saturday July 15th, 2023 at the Marriott Hotel in Orlando, Florida. Sairaj Dhople and Manish Singh will assist with the interview. Dr. Chandorkar, during today's interview, we are especially interested in your early work on droop control and how it was later carried forward into standard approaches to parallel operation of inverters on today's grids. We'll begin with some introductory questions and general background information about you. So, if you would, please describe your educational background and your professional positions in the field of electrical engineering.

Mukul Chandorkar (00:00:45):

Thanks, Julie. I was glad to be here for the interview. I first, well, I, well, my undergraduate degree was from India, in the Indian Institute of Technology in Bombay. I've worked for several years in India, in different Indian companies for a while, and then got my PhD from the University of Wisconsin in Madison. After that I worked for several years more at ABB corporate research in Baden, Switzerland, working mostly with the drives, high, medium voltage, high powered drives. And then I've joined academics back and became a professor in IT Bombay. That's been my journey.

Julie Cohn (00:01:32):

So, do you see yourself as more of an academic or as an industrial person or a little bit of both?

Mukul Chandorkar (00:00:41):

It's a bit of both, <laugh> that's the way things have happened. But I think the two do inform each other quite a lot. And I mean, the academic approach in developing products has been really useful for me as well as experiences in industry have shaped the way I teach courses and work with students. So, it's been both ways. Yeah.

Julie Cohn (00:02:05):

Do you currently have a big research group at your institution?

Mukul Chandorkar (00:02:10):

We have well, there are about four of us faculty members in my group. And together we have several students that way. So, individually, at the moment, I'm sharing students with several other faculty members as well.

Julie Cohn (00:02:25):

Oh, and are there any current collaborations with industry?

Mukul Chandorkar (00:02:30):

Oh, yes, absolutely. Yeah. We work quite closely with industry, especially on the new product development kind of activity. So that's been going on, yes. Yeah.

Julie Cohn (00:02:42):

We'll turn to some questions now related to your personal contributions to power systems control. What has been the most important technical problem you've tackled?

Mukul Chandorkar (00:02:53):

<laugh> Yeah. Well, paralleling of inverters in the year 1991 was not easy. There had been prior work on parallel operation of inverter. The main thing was to do it without having any communication between the control system, the, or having them synchronized in any way, without the use of communication of control signals. So we had done a good amount of literature work on this, and found out that UPS manufacturers had already looked at the problem quite a bit, but there weren't really any solutions out there that looked at distributed systems which could be made to work together without the use of communication of control signals or even measurements between them. So, that is what we are sort of set out to figure out how to do. And yeah, that was an interesting and difficult problem to tackle, I think. Yeah.

Julie Cohn (00:04:02):

Why was it important to develop a way for these devices to operate in parallel without communication?

Mukul Chandorkar (00:04:12):

That's a good point. I mean, so I think the critical reason was that then they could be located anywhere, basically. And would essentially, it was a question of coming up with a way of making systems modular in a way, in a sense that you could just put them anywhere on a network, and then they would work on the basis of only local measurements. And then they would work each unit working on the, on the basis of its local measurement would affect the system. And that would be picked up by some other system also on the network, which would also work on the basis of its local measurement. And the whole thing would sort of somehow be fine. <laugh> That was the point. Yeah. So that was the important part. So

Sairaj Dhople (00:05:03):

So, you said you looked at UPS as an application which drove this. Was that information easy to find? I mean, you did hint that this was in the domain of industry, right? Yes. So, did you have to talk to manufacturers in order to get an idea for what they were doing?

Mukul Chandorkar (00:05:20):

It, so turned out that several companies had written papers on this, presented them in conferences, which is quite a good thing, so there was a good amount of information available from industry, especially in conference proceedings that way. And there were several techniques that were being looked at and essentially things like sharing of measurements was one approach that many companies had been trying, rather than sharing of control signals. So, you share a common measurement, so everyone, every unit on the network knows what the other unit is measuring, and with some idea of how the other unit is going to use that measurement, you could then decide on your unit what you would want to do. That that was the approach that a few of them had done. And it had sort of worked pretty well in some cases. There was a good amount of work that way. Then.

Sairaj Dhople (00:06:16):

So, what got you excited about this problem? I mean, it's quite specific, right?

Mukul Chandorkar (00:06:21):

Yes. Yeah. So, paralleling of inverters was to increase current ratings, for example, has been done for quite a while. Yeah. But then trying to see if we could do it with inverters far away, well, not far away, but even even on, on the same network without sharing controls. I mean, that was, that was one of the key things. So, it looked like an interesting, first of all, an interesting academic problem to look at, because it had not been done so thoroughly before. And so that's what started the whole thing. And then we, when we presented our findings in the first conference, that was in 1991, the IAS conference of 1991, we got feedback saying that this is important work, because that's the way things are going to evolve with the inverter-based source interfacing and things of that kind. So, then we went on, went on ahead with that. That was, that's how it happened.

Sairaj Dhople (00:07:30):

Can you say a little bit about that venue? Were you a fresh graduate student? Was this your first conference? Do you remember who was in the audience?

Mukul Chandorkar (00:07:37):

Absolutely. Thanks for asking the question. It brings back lots of memories. <laugh> So, this was the industry, IEEE Industry Application Society, annual general meeting. And this was in 1991 Dearborn, Michigan. It was my first conference. I was nervous. <laugh> And they were all industry stalwarts in the, in the audience. That made me even more nervous. And the kind of questions that were asked and the amount of interest shown during and after my presentation, sort of gave me a little bit of confidence that perhaps you're on the right track that way. Yeah. So, yeah, the memory is quite fresh in my mind. <laugh>

Julie Cohn (00:08:26):

What was going on in the industry at that time that made this important?

Mukul Chandorkar (00:08:32):

So, the UPS industry was looking at it very seriously for,

Julie Cohn (00:08:36):

Let, let me just interrupt for a moment. And UPS means?

Mukul Chandorkar (00:08:40):

Uninterruptable power supplies, the Uninterruptable power supply industry. Thank you. <laugh> Yeah. Was very much interested in this at that time. One of the reasons they were interested in was, essentially, they wanted to look at ways of using their existing uninterruptable power supply units, UPS units, and just doubling them, tripling them to get higher and higher power ratings. That was one thing. Also, at the same time on the DC paralleling side, I mean telecom power, telecommunication power supplies, power supplies for telecom communication equipment, were being built at higher and higher power ratings that way. So, the UPS in the, yeah, the UPS industry was essentially interested at that point in time in increasing the power rating of its offerings without having to re-engineer and develop a full new product. And there were already several offerings on the market using these concepts, but without, it's still with communication and things like that, that way. Yeah.

Julie Cohn (00:09:53):

So how did you tackle the problem?

Mukul Chandorkar (00:09:56):

<laugh> So, the first thing we did was simulation. And ideating was the first thing. And my advisor, professor Deepak Divan, it was really nice to get insights from him as well. And so, what we had, the way we started approaching this was essentially by looking at papers, literature on the way how inverters were connected in parallel with the grid. So, the grid and an inverter, working in parallel, was the first system we sort of looked at. And then the extension of that was two inverters working in parallel with the grid. So, and then the next extension was, if you remove the grid, what happened? And that's how it happened. So, in these three stages is what I would say we worked in, and in the process we came up with different ways of even controlling the inverter as well. That was all there in the 1991 paper, but that inverter control measure is not really talked about too much, that one.

Sairaj Dhople (00:11:08):

So were you aware of, at the time, about how closely your solution approach mimicked the operation of bulk power systems, specifically droop control and synchronous.

Mukul Chandorkar (00:11:20):

Generators? To a good extent. I was, this is, so, especially when I was looking at the interconnect with the power system, I did take a look at this book by Nathan Cohn, I must say. That was <laugh> a really important book for me. I'd studied about power system control and, as a topic in my undergraduate courses and things. But the, but really the first operational and practical aspect of how these things work in parallel was from the book by Nathan Cohn, and I still have that book with me. It was, so that sort of started me out. So I was, to a good extent, aware of the power systems practice thanks to this book. Yeah.

Julie Cohn (00:12:13):

In addition to Deepak Divan, were there others with whom you collaborated on this?

Mukul Chandorkar (00:12:20):

There was not to the same extent, but yes. There, faculty members at the University of Wisconsin, there was Professor Alvarado, Fernando Alvarado, with whom, he was on my research committee, progress committee, and also Professor Bob Lassiter. Both of them, yeah. So, it was useful to have discussions with them, absolutely. Yes.

Julie Cohn (00:12:51):

Did you hit any dead ends while you were pursuing this?

Mukul Chandorkar (00:12:54):

<laugh> I don't think there were—there were not really dead ends, but difficult parts were there. Experimentally, I mean, in simulation things worked. The difficulty, I mean, somehow instinctively, you know that it's going to work, <laugh> but in putting it into practice was essentially the difficult task. Getting two inverters to work nicely with each other the first time when you don't know whether you, you connect them together and things going to blow up or not. <laugh> That was—so it was a practical aspects of it rather than the conceptual things. Conceptually, we knew to work that.

Julie Cohn (00:13:40):

And did they blow up?

Mukul Chandorkar (00:13:41):

No, they did not. <laugh> That was one of the, that was <laugh> one of the happiest moments of my, the first time when things connected, worked fine. <laugh> That's great.

Sairaj Dhople (00:13:52):

Did you do the simulations and build the hardware? Like, and has that been sort of a feature of your research, both the simulations and the hardware?

Mukul Chandorkar (00:14:01):

That's correct. Yeah. So, the simulation the entire simulation of a system of, well, relatively manageable system, and the correspondingly rated hardware Yeah. With, with inverters. So, the so in the, in the lab in Madison, we already had inverters that other people had built. So essentially, I used the same inverters and modified them to suit parallel operation, putting inductors on the output side and things of that. Yeah, yeah.

Julie Cohn (00:14:35):

After the IAS meeting in 1991, were there further conferences or publications where this work was developed? Repeated?

Mukul Chandorkar (00:14:46):

Yes. Yes. Yes. So, in the 1991 IAS conference, what we had done was essentially looked at the modulation method that would be suitable for inverters connected to the grid. And then we had used that modulation method to look at situations where inverters were connected to each other. And then in the next time we had done it, done, the extended the work was essentially, I think in the APEC conference of I can't remember the exact year now on that one, but that was an extension of the work to larger systems. And then that was basically an architectural kind of a paper. I mean, what larger systems could look like that would that, would work well with the schemes that had been developed for the smaller systems that way. So that was the first extension of the work. Yes.

Julie Cohn (00:15:44):

And then it was eventually adopted widely, your approach,

Mukul Chandorkar (00:15:50):

So, it seems, yeah. Yeah.

Julie Cohn (00:15:54):

I assume this is still the foundational tool for how inverters operate today.

Mukul Chandorkar (00:16:01):

I think, yes, to a large extent, but I think there are many other system control systems are also in place now. So Sairaj, for example, have done a good amount of work in self-oscillatory systems, that kind of thing. So, there are, there are different approaches as well.

Sairaj Dhople (00:16:26):

But because what happened after that? You graduated, you were blissfully unaware of what you had created, and you moved on to industry and you never looked back, or did you pay attention to what was going on?

Mukul Chandorkar (00:16:36):

No, I did pay attention to what was going on, but excuse me, after I graduated from medicine with a PhD, I had always been interested in motor drives for one thing, induction motor drives. And so,

Sairaj Dhople (00:16:52):

What, what drove that interest, if I may ask?

Mukul Chandorkar (00:16:55):

Well, I had done these excellent courses on machines, machine modeling and analysis and control by Professor Lipo, and I was a teaching assistant for Professor Novotny at the University of Wisconsin when they had taught those courses a few years later after I'd taken them. And those were excellent courses, and that's, I think that's what started my interest in motor modeling and control. So, I had always sort of looked for an opportunity to do some practical work with, with motors and motor control. So, when I—and I must also say that there were not too many industry jobs that were being offered for people who could parallel inverters. So, it was just starting out, but parallel inverters without having them talk to each other, especially. So, what, that way—

Julie Cohn (00:17:57):

There wasn't a whole industry conference where people passed the resumes around?

Mukul Chandorkar (00:18:02):

<laugh> No, there was absolutely not. So, when I got a job offer from ABB in Baden, Switzerland I just took it. And luckily that was in corporate, ABB corporate research, which sort of gave me the flexibility of working with different parts of the company. And one of the first things I did was essentially look for an opportunity to work with the drives people. So good part of my time I spent with the group that was developing medium voltage drives in ABB industrial systems, that way. But I was all the time following up on what's happening on this, especially with the modulation method that we had sort of worked on, but was never used by anyone, still not being used by anyone, unfortunately. Really? Yes. And, but still, I mean, it was, it was in, so I did keep touch. I did keep in touch with what was happening. Absolutely. Yeah. So just a—sorry. Oh, carry on. It's just that I wasn't actively working on that at that time. Yeah.

Julie Cohn (00:19:10):

Why do you think the modulation method was not used by anybody?

Mukul Chandorkar (00:19:16):

I think I didn't disseminate it so effectively. I have a paper on that though, but it has problems as well, <laugh> to say. But then those are not insurmountable. It was—I was glad to see that it was discussed in a few textbooks on pulse modulation, at least that part. And, it was sort of, it was inspired by earlier papers, by the papers on, in large inverters connected to the grid. It was basically talking about how you can connect large inver-, control, large grid connected inverters at very low switching frequencies. And so, I had sort of taken that and modified it for motor drives, that that was the thing. Yeah. So yeah, no, there are other methods of doing it, so I don't think that's, there's so much interest in that anymore right now. Yeah.

Julie Cohn (00:20:25):

So, is there work you're involved in now that still refers back to this earlier droop control work?

Mukul Chandorkar (00:20:34):

Yes. Lately, yeah. My students, after all this, after I went back to academics, my students did do some work on that. But I think the rate at which everyone is working on it right now, I think it is very difficult to make any impact anymore on, on that. Yeah. That's, that's so at the moment, no, I'm not going to go back to work on that.

Manish Singh (00:21:03):

When you first chose to work on it as a graduate student, was it just your problem? You didn't know that it may have such a big impact, or you knew that we are aiming to solve a very big problem, and you shot for the big thing?

Mukul Chandorkar (00:21:14):

No, I didn't have the big picture at that time. It was too difficult to see that, but it was an extremely interesting problem. Yeah, absolutely. And I, you could see the complexity of trying to do, to analyze this when and, what, and essentially trying to come up with a set of very simple rules that would ensure something globally by looking at something very locally. That was a big challenge. It was, it was not easy to do. And coming up with rules on how to ensure that is one of the keys. We try to do that. And how to decouple the control loops, how to ensure that the control the inner control loops of one converter do not affect or do not interact with the loop of another inverter, but they interact only at the level at which we tell it to interact that way. So, coming up with those rules and analyzing them it was a, it was a very interesting thing to do that way at a big system level. So it was more of the intellectual challenge, that thing that drove that. The feedback that we had gotten in nine, in the 1991 IAS conference sort of gave us the confidence that this is something really worth pursuing. But I don't think anyone really thought about the really long-term implications of that.

Sairaj Dhople (00:22:43):

So, that's a very good point. So, you feel like there was, you had this initial work, there was interest, but maybe there was a period of time where this, people were sitting on it and thinking about it, and the industry was, Yes, was gravitating in a particular direction. And then do you think that, do you remember like an inflection point at which as you opened up publications, all you could read about was, was droop control when it came to this topic?

Mukul Chandorkar (00:23:12):

There? Yes, there was, there, there was a very clear inflection, personally for me, when I figured out that something's going on here. And that was when I was working in ABB, so with just a few months before I left ABB to join academics, there was a there was a proposal floating around on controlling inverters in a microgrid in the ABB corporate research using communication, all kinds of sophisticated communication techniques and things like that. And I was not really aware of that proposal, but then one of the team members found out that I had this paper back there, and then they asked me to make a presentation, and I made a presentation in the corporate research center. And I made a statement saying that whatever we do in a complex system, basic survival should not depend upon communication. So that, I think, really got people, people's attention. And then they, I think they, I'm not sure what they did with the proposal after that, because I sort of left the company by then. But I think that was when I realized that there were lots of people looking at these kinds of things. And after that, I began to see lots of papers coming out from different groups all over the place.

Julie Cohn (00:24:44):

Do know what about what year that would've been?

Mukul Chandorkar (00:24:47):

This was in 1995. I'm sorry, this was in the year 1999. 1999. That's when you left ABB? That's when I left 2000. Yeah. Early 2000.

Julie Cohn (00:25:00):

So, do you have an understanding that you left the company shortly thereafter? Did you get much feedback after you gave your presentation? Because it sounds like you were challenging them to rethink how they were planning to approach things.

Mukul Chandorkar (25:14):

No, I did not get any feedback officially. I mean, I had friends there, so I also kept talking to them. So yeah, I know that they did, I think they did work on it so much, but I'm not aware of to what extent. And so, I didn't get any, any official feedback on that. Yeah.

Julie Cohn (00:25:32):

But then you, you started to see across, Yes, the publications that this was the hot topic. Yes,

Mukul Chandorkar (00:25:39):

It was a hot topic, yes.

Julie Cohn (00:25:40):

Did you see your work getting cited over and over again?

Mukul Chandorkar (00:25:43):

Yes. <laugh> That was very satisfying. <laugh>

Julie Cohn (00:25:46):

That's great.

Mukul Chandorkar (00:25:47):

Yeah. And so also there were several companies working on this thing called the Power Electronic Building Block or PEBB as it used to be called. And that was essentially making modular blocks of power, electronic switches and controls and protection inside them. And you could just string them together in parallel, plug and play kind of thing. And there were bricks or something that, kind power electronic building blocks. The idea was to build converters of any size and any power rating by just putting blocks, the standardized blocks together. So, there was a good amount of work going on especially in the United States, I think in the, in the, in the mid 1990s. That was, and I think several European companies were also sort of interested in that concept 'cause it was a very practical thing to do. And central to all of that was essentially the ability to just put things together and work in parallel. And communication would be an added advantage. But even without communication, something goes wrong, this thing would be reliable enough to function by themselves. So that's, again, when this droop-based concepts came into play, rather began to be looked at carefully not only by academia, but also by companies, by industry that way.

Julie Cohn (00:27:21):

Was that an application primarily intended, I mean, physical product, but primarily intended for the renewables industry or for storage or for other completely different types of applications?

Mukul Chandorkar (00:27:34):

I, applications, not necessarily specifically for renewables, because I don't think renewables were that so big at that time. Yeah. That point in time. Not even the automotive. So, I think it was just a way of building bigger converters, a new way of building bigger converters. And I do know that, well, I think the military was also interested in this because it gave you a way of putting things together very quickly, a large, larger and larger system modularly very quickly. And it was also, it, this concept would've been also reliable. I mean, if one unit fails, it's still okay. Everything else keeps working. So, it was sort of robust in the sense of not failing completely mm-hmm. <Affirmative>, if a component failed, unlike a large single inverter, if something fails, then that just—so, there was a lot of interest in ultra reliable kind of power supplies that were built on this modularity concept. And one of the keys to that was essentially making sure that they all work very well in parallel. So, this was one of the, so the droop control thing was one of the methods that people were looking at for power electronic building blocks as well, including industry.

Sairaj Dhople (00:28:56):

I'm sorry. But on several occasions, you've talked about putting things together, right? Like, I get this image of you tinkering, assembling things, building things. Is this an interest that you've always had since your childhood, or was it, and you know,

Mukul Chandorkar (00:29:13):

Well, thanks, thanks for asking the question. Yeah, yeah. Tinkering is something that I've always liked, working with my hands that way. Soldering things and that. Yeah, yeah. I've been building stuff ever since I was, ever since I can remember, I think. And I still do <laugh>. So—

Sairaj Dhople (00:29:33):

<laugh> is it just your natural curiosity finding an outlet, or did you have other heroes growing up that you were inspired by to pursue that sort of,

Mukul Chandorkar (00:29:46):

Yeah. I mean I can't remember the origin of that, but I think, but they were—no, I really can't say. I was just some, it was just interest. I think just take things apart. As a kid, you would take things apart and that thing stayed on, <laugh> that interest stayed on. You can't always put it back together again. But it's still okay. I think I figured out. <laugh> Yeah. So, it has been there for, yeah.

Julie Cohn (00:30:21):

Are there other technical topics that captured your imagination as completely over the years as this one?

Mukul Chandorkar (00:30:30):

Well, as I said, motor drives, that was—yeah. I still have a lot of interest in that. And I've had students doing their PhDs with me on motor drives as well. So, I've, I've worked on modeling faulted machines, for example, developing transient models of faulted machines, trying to see if they if their transients contain any information on the kind of fault that is there in them on the basis of the models that we develop. So, things of this kind. So, motor drives has been with me for a while that way. It's been a very interesting thing for me. Also, multi-motor drives and things like that. Yeah.

Julie Cohn (00:31:13):

Manish and Sairaj. Are there other questions on this looking back part of the interview that you'd like to ask?

Sairaj Dhople (00:31:24):

I guess if I had to ask one more question in this space—you're well aware of how renewables today is somehow driving a lot of interest in this particular scheme of droop control: do you have any thoughts about that or the impact that this one control method might potentially have on solving, quite admittedly, a societal scale problem?

Mukul Chandorkar (00:31:52):

Well for one thing, it's a very easy thing to understand and implement as well. So, I think doing so for, if, if a system is extremely complex, it is best to use understandable <laugh> and easy things that are easy to do it rather than the complexes, because you don't know what the consequences would be. So, to that extent, I think it's fairly easy to understand. And I think that's its power. And I think perhaps one should take closer look at how it can be sort of developed and things like that. Yeah.

Manish Singh (00:32:38):

On the, on the droop related paralleling of inverters, if I look at that problem, it's a very broad problem in terms of how you can take an attempt at that in the sense that one could look at it from a system theory, stability, convergence kind of vantage point, or one could look at effect of measurement noise, implementation issues. . So, when you first approached it, where did you stand on the spectrum of theory and application and implementation and the criticism? Did you face, like, when you were getting the feedback, was it like, can you prove this? Or was it like, can you build this?

Mukul Chandorkar (00:33:10):

So, we started with building it for sure. I mean, so a simulation and building, building it, and found that it worked, at least for the system that we were working with. And then we looked at larger and larger systems, first of all, with analysis, well, simulation and analysis, and sort of developed the complexity more and more. We also did a, we also did a good amount of ana-, well, stability analysis and things of that kind on that but that came a little later on. There were implementation issues as well on how to best implement it. Well, especially in the laboratory, kind of a setup. When you're trying to do all of these things paralleling things and stuff like that you have to, you typically would have a single power supply feeding both inverters and there's a possibility of circulating currents and things. So, understanding those kind of things and getting a set-up to work, the practical aspects were essentially what took up most of our time in the beginning. But once those were sorted out, I think then we started looking at the extensions and the analysis further, more complex simulations and things of that kind. So, the analysis, I think, came pretty much late into the game for this. Yeah.

Manish Singh (00:34:34):

And once the topic became more famous and gathered so much attention, were you or your collaborators contacted by other people from the field looking for collaborations? Or can we do this? Can we do that?

Mukul Chandorkar (00:34:44):

Yes, yes. That did happen. And well, I began to get requests for copies of my thesis more and more, <laugh> and I would be happy to sort of give them copies and things of that kind. And, so, and then there were a few collaboration requests as well. It did work out, but to some extent, yes. Yeah. So that's been happening.

Julie Cohn (00:35:17):

Looking ahead, would you approach the challenges of adding grid forming inverters the same way you approached these kinds of problems in the past?

Mukul Chandorkar (00:35:32):

I—that's a good question. Looking at how we've come to this point, looking at how to get grid forming inverters into place there, generally speaking, I think that's a very personal approach. Different people approach extension of this kind in different ways. The way I do it is essentially start with a mentally intellectually tractable problem first, figure out the basic concepts of this, of how to go about, well, getting them to work together and things like that. And then look at bigger and bigger and bigger systems, adding more and more complexity, non-idealities and stuff like that. So, build up from the ground of its smaller units rather than think of the entire system first, and then try to figure out what's happening there. But I think different people have different approaches to these things, but this, that's what I would do anyway.

Julie Cohn (00:36:37):

Thinking about some of the original challenge of making these inverters work together without communication and the motor drive challenges and so forth, are there external matters that influence the success of the technical solution? For example, regulatory matters or the way markets are designed or things like that?

Mukul Chandorkar (00:37:12):

I'm not really sure. I don't know, because I've not really given it too much thought, <laugh> it just looked like an interesting thing to do. So, I <laugh> that's what drives, I think most of us, I suppose. But that's a good point. I mean there are, there would, I mean, for example, one aspect of the one regulatory aspect would be essentially restoring frequencies once they go down on a droop. And even that has to be done in a decentralized way without communication, if possible. So, there were those kinds of challenges, I think, that those do need to be taken into the technical solution as well. But I think that would be an extension, not the core of the problem that we are trying to solve there.

Julie Cohn (00:38:09):

If a general audience could walk away with one important thing to know about droop control, what would it be? <laugh>

Mukul Chandorkar (00:38:17):

It's easy. <laugh> And that's important. That's what I would say.

Julie Cohn (00:38:25):

I like it. Yeah. Do you have other questions you'd like to ask?

Sairaj Dhople (00:38:30):

I do. Mukul, you've shared with me your thoughts on sustainability very broadly defined. And I think for the benefit of everyone else who's not been as fortunate as me to have spent some time with you and hear your thoughts, I'd just love for you to share just your thoughts on what sustainability means for you and how you've thought about it in the context of electronic systems and engineering in general.

Mukul Chandorkar (00:38:59):

Yeah, that's a good point. So, there are several aspects to it. First of all, energy usage and renewables and things like that is one thing. But I think one of the things that I think we talked about sometime back was essentially trying to build sustainability into product design. I mean, in a sense, how do you design a, let's say an inverter or whatever, for example, an inverter, so that at the end of its life, you could make use of, you could take care of it properly that way without letting it go to waste or something of that kind. And there are, excuse me, and there are technical ways of doing that as well. And I think we need to explore some of those things.

(00:40:01):

For example, one component that contains hazardous material could be emulated by power electronic switching, plus another component that does not contain hazardous material, something of that kind. And there are examples of these things that could be done. I haven't really worked on all that so much, but I think it's worthwhile looking at those kinds of things. So, the combination of the switching that power electronics provides us, along with a set of benign passive components, gives us the ability to emulate several things, the behavior of several components that could potentially be hazardous that way. So, I think one has to look at these kinds of possibilities. It's not easy, and it's probably not going to happen anytime soon. But I think, again, it's an interesting problem to tackle. And that extends to not only smaller systems, but even bigger modular systems.

(00:41:04): I mean, things like layout of components on a printed circuit board, for example, on the, keeping in mind that at some point in time that has to be recycled or depopulated or things, things of that. So, I think many product design approaches do not factor these things into their product design. It's functionally cost wise, space wise, weight wise, is what they look at. But in addition to that, I think perhaps also take a look at what happens, how do you design it so that it is easy to take care of in the end of it, at the end of its life that way. So, we did some literature search on this. We started out some work on this, but there's not much available. And there's not too many people I can discuss, except for people like you. There's not too many people. I can discuss these things with—<laugh> so how it works.

Julie Cohn (00:41:59):

Do you think the lack of thinking about the lifecycle of the materials is typical, more typical of electric engineering than other fields? Or is that sort of a broad,

Mukul Chandorkar (00:42:16):

I don't really know so much about the other fields, but I don't think there's anything special about electrical engineering as far as that is concerned. I think it applies to pretty much everything.

Julie Cohn (00:42:27):

Well, the thing about electrical engineering is you deal with a substance that's invisible,

Mukul Chandorkar (00:42:33):

<laugh>. Oh, yes. Yeah. <laugh>

Julie Cohn (00:42:35):

And a civil engineer might be dealing with dirt, or bricks, or something like that. So yes, I don't know if that makes a difference in the extent to which materiality comes into, Yes, what you think about—

Mukul Chandorkar (00:42:48):

I, my understanding the way, at least the way I perceive it, is that in electrical engineering, we have a lot of flexibility which we could use, degrees of freedom, so to speak, which we could use to address these kinds of issues, which, which other domains may not have the same level of flexibility to get a particular functionality. But I think in electrical engineering, especially in electronics and things of that kind, there is a good amount of flexibility to achieve the final aim in multiple ways. Yes. And perhaps that could be utilized to make one of the constraints that, it has to be sustainable, something like that. Yeah.

Julie Cohn (00:43:35):

Interesting. Yeah.

Mukul Chandorkar (00:43:37):

So—

Sairaj Dhople (00:43:41):

Do you have any words of advice for the next generation of power engineers, power system engineers, power electronics engineers?

Mukul Chandorkar (00:43:49):

<laugh> Words of advice? It's hard. That's hard to give. It's hard to give advice to anyone, I think. But, but it's an interesting field, I think, and there's lots to be done. It's also, I mean the social impact of the field, like this is also potentially very large. And I think everyone, all electrical engineers can find something or the other in the field that will, some aspect or the other in the field that will motivate them to work hard, I think. So, we should just look for those aspects, I think. With sustainability, so be it. If it is <laugh> paralleling inverters, so be that <laugh> that kind of stuff, I suppose. Yeah.

Julie Cohn (00:44:43):

Great. Thank you so much. We really appreciate your time.

Mukul Chandorkar (00:44:46):

Thanks a lot for having me. This was—for me, it was an enjoyable conversation.

Julie Cohn (00:44:51):

Oh, good. I'm glad to hear that.

[End of Interview]