Rajkumar Palaniappan

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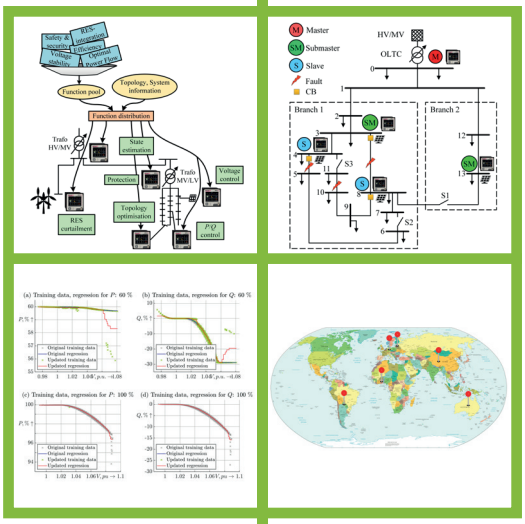
Band 26



Dortmunder Beiträge zu Energiesystemen, Energieeffizienz und Energiewirtschaft

Coordinated voltage control in active distribution grids using distributed field measurements

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by

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Abstract

The integration of distributed energy resources and new loads such as electric vehicles and air conditioners has drastically increased in the last decades. Although the increase of distributed and often renewable energy sources makes sense from an environmental perspective, this new paradigm poses significant challenges to distribution grids, which were not initially designed for bidirectional power flow. The distribution system operators must expand their grids or develop intelligent control algorithms. Another factor to consider is the digitalisation of the distribution grids with the advancements in information and communication infrastructure. In order to determine the exact system state and control the flexibilities in real-time, field measurements are essential in the distribution grid, which were not available in conventional distribution grid operation.

Considering these challenges, this thesis proposes control algorithms for real-time control of the various flexibilities using distributed measurements to prevent voltage and thermal violations, thereby driving towards distribution grid automation. The control algorithms are configured using IEC 61850 data models, which were not done in previous research, and applied to a selected research prototype. Such an implementation provides the advantage of modularity by separating the hardware and software, which essentially makes the software easily portable and independent of the hardware. Considering the increasing reliance on the data transmission between the various components for grid operation, system and communication outages in the distribution grid are inevitable in the future. This thesis also proposes individual countermeasures to mitigate such failures and make the algorithms more robust by implementing hierarchical control strategies and using data-based learning methods.

The implemented algorithms are experimentally verified using a real-time simulator and an analogue grid model in the laboratory. In order to analyse the effectiveness of the implemented algorithms, they are experimentally verified in various benchmark grids. To demonstrate the applicability and versatility of the algorithms, they are applied on international grids. The results of the hardware-in-the-loop simulations and the laboratory test show that the implemented algorithms could support the distribution grid operation by providing voltage control using real-time control of the flexibilities. The implemented algorithms could be validated in reality when the local grid policies allow real-time control of the distributed energy resources.

Kurzfassung

Die Netzintegration von dezentralen Energiequellen und neuen Lasten wie Elektrofahrzeugen und Klimaanlagen hat in den letzten Jahrzehnten zugenommen. Obwohl die Zunahme von dezentralen und häufig erneuerbaren Energiequellen aus ökologischer Sicht sinnvoll ist, stellt diese Transformation der Energiesysteme die Verteilnetze, welche ursprünglich nicht für einen bidirektionalen Leistungsfluss ausgelegt waren, vor erhebliche Herausforderungen. Die Verteilnetzbetreiber müssen ihre Netze ausbauen oder intelligente Steuerungsalgorithmen entwickeln und implementieren. Ein weiterer zu berücksichtigender Faktor ist die Digitalisierung der Verteilungsnetze mit den Fortschritten in der Informations- und Kommunikations-infrastruktur. Um den genauen Systemzustand des Netzes zu ermitteln und die Flexibilitäten in Echtzeit zu steuern, sind Feldmessungen im Verteilnetz unerlässlich, die im konventionellen Verteilnetzbetrieb nicht zur Verfügung waren.

In Anbetracht dieser Herausforderungen werden in dieser Arbeit Regelungsalgorithmen für die Echtzeitregelung der verschiedenen Flexibilitäten unter Verwendung verteilter Messungen entwickelt, um Spannungs- und Stromverletzungen zu verhindern und somit die Automatisierung des Verteilnetzes voranzutreiben. Die Regelungsalgorithmen werden unter Verwendung von IEC-61850-Datenmodellen konfiguriert, was in früheren Forschungsarbeiten nicht der Fall war, und auf einen ausgewählten Forschungsprototyp angewendet. Eine solche Implementierung bietet den Vorteil der Modularität durch die Trennung von Hard- und Software, was die Software leicht portierbar und unabhängig von der Hardware macht. In Anbetracht der zunehmenden Abhängigkeit von der Datenübertragung zwischen den verschiedenen Komponenten für den Netzbetrieb sind System- und Kommunikationsausfälle im Verteilnetz unvermeidlich. In dieser Arbeit werden daher individuelle Gegenmaßnahmen vorgeschlagen, um solche Ausfälle abzumildern und die Algorithmen robuster zu machen, indem hierarchische Kontrollstrategien implementiert und datenbasierte Lernmethoden verwendet werden.

Die implementierten Algorithmen werden experimentell mit einem Echtzeitsimulator und einem analogen Netzmodell im Labor verifiziert. Um die Wirksamkeit der implementierten Algorithmen zu analysieren, werden sie in verschiedenen Testnetzen experimentell überprüft. Um die Anwendbarkeit und Vielseitigkeit der Algorithmen aufzuzeigen, werden sie auf internationale Netze angewandt. Die Ergebnisse der Hardware-in-the-Loop-Simulationen und der Labortests ergeben, dass die implementierten Algorithmen den Betrieb des Verteilnetzes durch Spannungsregelung mittels Echtzeitsteuerung der Flexibilitäten unterstützen können. Die Algorithmen könnten in der Realität validiert werden, sofern die lokalen Netzrichtlinien eine Echtzeitsteuerung der dezentralen Energiequellen erlauben.

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There is only one name that appears on the first page of this thesis, but there have been an enormous number of people who have helped me over the years. I feel grateful to acknowledge all those responsible for making this a memorable experience.

First and foremost, I would like to thank Prof. Christian Rehtanz for giving me the opportunity to pursue my PhD at the Institute for Energy Systems, Energy Efficiency and Energy Economics (ie³) at the TU Dortmund University. The freedom and trust that I experienced over the years under his supervision made me realise that he is an excellent mentor and always had time when I needed a discussion. I have learned to say 'no' artistically without actually using the word 'no' from him. My sincere gratitude to Prof. Marco Liserre for accepting to be a co-advisor and for his constructive comments for the betterment of the thesis.

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I believe that the working environment determines the quality of the work. In that sense, I would like to thank the wonderful atmosphere created by Christian and Ulf at the Institute ie³. Managing around 50 employees is not an easy task to do and still, they both have done it with ease for the past few years. It is only because of this compatible working atmosphere that things run smoothly in the various research groups.

During the course of this thesis, I have been blessed to encounter so many people who helped me be in the position I am now. When I had no idea what to do after my masters, my friends Dr Muthukumaran Venkatachalapathy, Dr Nisha Mohan, Dr Jayakumar Samydurai, Dr Dineshkumar Dusthakar inspired me to go for a PhD. I always believed that a PhD is only for brainy people and I didn't have the brains for it (I still can't believe I wrote a PhD thesis). Being a part of their journey helped me understand the world of academics a bit better.

I want to thank Dr Björn Keune for paving my way into the Institute ie³ with the project group. As an international student from Automation and Robotics, there were few options at that time to be a part of the energy systems research. Special mention to Dr Andreas Kubis for allowing me to be a part of the PESS conference, which allowed me to come in contact with Christian and know more people from the Institute ie³. I wish to thank Ms Wasila Al-dubai for all the help with the DAAD scholarships and for getting me involved in so many intercultural activities.

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During my master thesis, I got acquainted with Dr Dominik Hilbrich and (soon to be Dr) Björn Bauernschmitt. From being my thesis supervisors to being colleagues to being friends, it has been a complete journey with many ups and downs. They were available for brainstorming at all times and I remember having technical conversations at 1 am over beer. It would not be an exaggeration to say that I could complete my thesis only because of these two people. Dominik's in-depth technical knowledge and Björn's eye for detail are qualities that I aspire to get someday. They introduced me to VDE and I can write a separate book about that journey alone. As an international student in Germany, I can say that almost all of what I know about German culture and bureaucracy came from discussions with them. I feel fortunate to have worked with them.

My sincere thanks to my colleagues Sebastian Raczka and Dr Michael Steglich for being amazing teammates. Sebastian is more of the diplomatic type, whereas Michael has an opinion on things. I have learned a lot from our conversations about German idioms, history and politicians.

My colleagues, Dr Marvin Albrecht and Marcel Klaes, taught me to be relaxed and not to take everything so seriously. Over the years of seeing them in close circles, I feel that their casual attitude has rubbed off on me and I notice that I don't take too much pressure on myself as I did before. I am not sure if I can ever reach their level of level-headedness, although I hope I learned a few things from them.

I want to thank the colleagues who helped me with all the administrative and technical works. Thanks to Nicole Funke and Nina Ganser for organising all the paperwork and making all the important phone calls to the administration. Sven Seibt and Jan Elvermann took care of all the purchases, while Bernhard Dick and Tobias Loidl were very kind to patiently teach me about the IT stuff when answering my stupid questions. Although they work a lot from the background, all these people made my life easier, so I could concentrate on the research projects and special thanks to them.

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I was also fortunate to co-organise the German Russian Summer School in 2019. Christian and Ulf were in Russia on an official trip and I got to represent TU Dortmund University while visiting the German President, Dr Frank-Walter Steinmeier. So, thank you both for not being there.

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And finally comes the family. I am the last of 3 brothers and my mom always said during our childhood that she wanted a son who grew to be a medical doctor. Tough luck, she has to be satisfied now with two sons with academic PhDs and a third son with masters, all in engineering. I remember her saying when I joined my PhD.: “Yes, you will be a doctor one day, but just not the kind who is useful to anyone.”

Fun apart, they are my source of strength. Whenever I feel down, a short phone call with mom and dad brings the smile back. I'm not sure if the stress goes away, but somehow they have a way to make me feel better. My brothers and sisters-in-law, Arunkumar, Saranya, Ganeshkumar and Nacha, have always been the responsible ones and have allowed me the freedom to explore new things. I would not be here if it were not for them and I have to thank them for that. My nephews and niece Karthik, Vishal, Prasanna and Swathi have always been wonderful to play with. Being away for so long away from home makes me realise that the kids grow really fast, but still, I get to be a part of their lives with the video calls.

Finally, the people who I spend the most time with. My wife Priya and my daughter Yaalini. Priya has been a source of constant encouragement and has been with me through all my crazy days. She is continuing with her master studies with our daughter by our side. I can't even imagine if I would have the determination to study when in her place. She has sacrificed a lot for me over the years and has been a source of courage and reassurance. She provided a lot of motivation for this thesis by constantly asking the question: "When will you finish your ***** dissertation?"

I don't know where I should start with our daughter Yaalini. I wish I had her energy and capacity to learn new things and I would have finished the PhD in 2 years. After a long day's work, she waits for me to wash my hands and then hugs my legs and I long for that every day.

This thesis should serve as proof that I did listen to my various colleagues when they were explaining technical stuff to me. Let this show that I was not sleeping throughout the conversation and that the last five years have not been totally wasted.

Rajkumar Palaniappan

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