Final report

1.1 Project details

Project title	IDE4L-DK Top-Up
Project identification (program abbrev. and file)	IDE4L-DK Top-Up 12156
Name of the programme which has funded the project	ForskEL programme
Project managing company/institution (name and address)	Department of Electrical Engineering, Technical University of Denmark Ørsteds Plads, Building 348, 2800 Kgs. Lyngby, Denmark
Project partners	
CVR (central business register)	30060946
Date for submission	11-08-2019

1.2 Short description of project objective and results

The IDE4L-DK Top-Up project is to co-finance the research work on real time demonstration of the automation concepts, and optimal voltage control and congestion management of active distribution networks with DERs.

The dynamic tariff for congestion management of distribution networks with DERs were conducted in the real time digital simulator (RTDS) to test its pros and cons.
Optimal voltage control schemes were developed to maintain good voltages and resolving voltage violations within distribution networks by regulating reactive power of distributed generators (DGs) and energy storages and on-load-tap-changer (OLTC).

IDE4L-DK Top-Up projektet skal med-finansiere arbejde inden for realtids demonstration af autonome koncepter samt optimal spændingsregulering og håndtering af overbelastninger i aktive distributionsnet med DER enheder.
Fordele og ulemper med dynamiske tariffer, som håndtering af overbelastnings i distributionsnet med DER enheder, blev undersøgt gennem test i en realtidssimulator (RTDS).
Metoder inden for optimal spændingsregulering blev udviklet til at bevare god spændingsforhold og til at løse spændingsrelaterede overtrædelser i distributionsnettet. Disse metoder regulerer den reaktive effekt fra distribuerede el-producerende enheder (DG), energi-lagrer samt regulering af transformeres viklingskoblere.

1.3 Executive summary

In the project, real time demonstration of the efficacy of the dynamic tariff for congestion management was conducted, and three optimal voltage control schemes were developed for active distribution networks with DERs.

It was shown that the dynamic tariff is effective for congestion management of distribution networks with DERs in most cases. However, because the dynamic tariff is calculated by the direct current (DC) optimal power flow (OPF). In some cases, the dynamic tariff may fail to resolve the congestion. Therefore, it is important to allocate a certain margin of the line capacity to avoid overloading.

Three optimal voltage control schemes were developed to maintain good voltages and resolving voltage violations within distribution networks by regulating reactive power of distributed generators (DGs) and energy storage units, and on-load-tap-changer (OLTC). Model predictive control was used to optimize the reactive outputs of DGs and energy storage units and operation of the OLTC.
The distributed information synchronization (DIS) framework and distributed model predictive control are used to realize distributed optimal voltage control for distribution networks with DERs. The DIS framework can reduce the cost of the communication infrastructure. The DGs only exchanges information with neighboring units. It can improve the privacy protection. The voltage control performance is the same as the centralized scheme.

A double time scale voltage control scheme was developed to coordinate the slow and fast var/voltage control devices. The slow time scale voltage control is to regulate the OLTC, step voltage regulators (SVRs), and capacitor banks (CBs) to correct long term voltage deviations. The fast time scale voltage control is to regulate the active and reactive power outputs of DGs to reduce voltage fluctuations and capture as much renewable energy as possible.

The results can be used by the utility companies for integrating large scale distributed energy resources.

1.4 Project objectives

The objective of the IDE4L-DK Top-Up project is to conduct real time demonstration of dynamic tariff for congestion management of active distribution networks with DERs and develop optimal voltage control of active distribution networks.

The real time demonstration of the dynamic tariff for congestion management of distribution networks with DERs was conducted as a master thesis project. The master thesis project went well and delivered very nice results. It showed both the pros and cons of the dynamic tariff. A conference paper was published with the results from the master thesis project and it was presented at the Asian Conference on Power, Energy and Transportation Electrification 2016 (ACPET).

The optimal voltage control of distribution networks with DERs was planned to done by a PhD student. However, the PhD student was in a very stressed condition and cannot conduct the research work. Therefore, the project was delayed and a research assistant was hired to conduct the work.

The research assistant performed well and developed three optimal control schemes for distribution networks with DERs. We delivered the work planned although the stress condition of the PhD student was very unexpected. Three WoS journal papers were accepted in the top journal in the power system field.

1.5 Project results and dissemination of results

In the project, the efficacy of the dynamic tariff for congestion management was tested in the real time digital simulator in the PowerLabDK. Three optimal voltage control schemes were developed for the distribution networks with distributed energy resources (DERs).

1.5.1 Real-Time Test of Dynamic Tariff for Congestion Management

In the project, the efficacy of the dynamic tariff for congestion management was tested in the real time digital simulator in the PowerLabDK. It was shown that the dynamic tariff based on the direct current (DC) optimal power flow (OPF) can resolve the congestion in most of the time. However, it also has limitation. Due to the reactive power flow, the congestion cannot be resolved in some cases. The solution could be to use the alternating current (AC) OPF to calculate the dynamic tariff. Or a certain margin of the component capacity can be kept to deal with the extra flow due to the reactive power.
The test setup is shown in Figure 1.

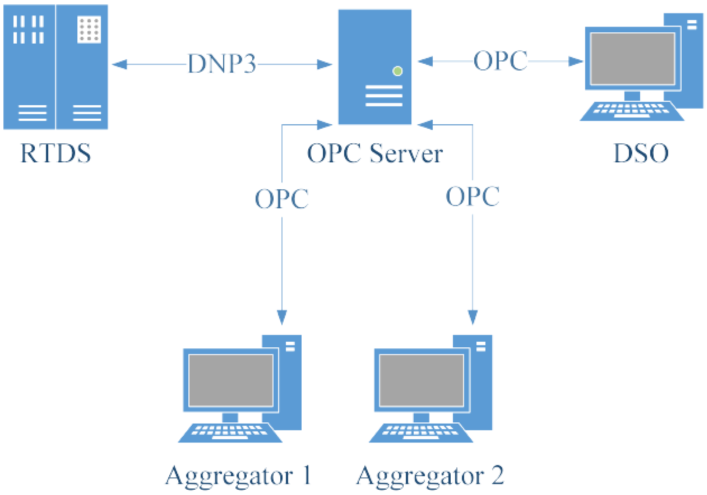

Figure 1 Test setup of the real time digital demonstration of dynamic tariff

The real time digital testing platform is capable of receiving load data calculated in the day-ahead dynamic tariff method, simulating the Rønne distribution network and returning power system stability parameters. These parameters are calculated by implementing the MV distribution network in a RTDS. The RTDS is a powerful hardware tool capable of calculating power system parameters in real time. When simulating the network in real time, the digital representation emulates an analogue testing situation.

Through simulation of a real power system in the RTDS, control mechanisms and equipment can be tested without interfering with the general operation of a real power system. The results from the RTDS study are to a high extent equal to results from implementing methods and equipment in a real power system and can be used to evaluate their efficiency. The flowchart of the testing the dynamic tariff is shown in Figure 2.

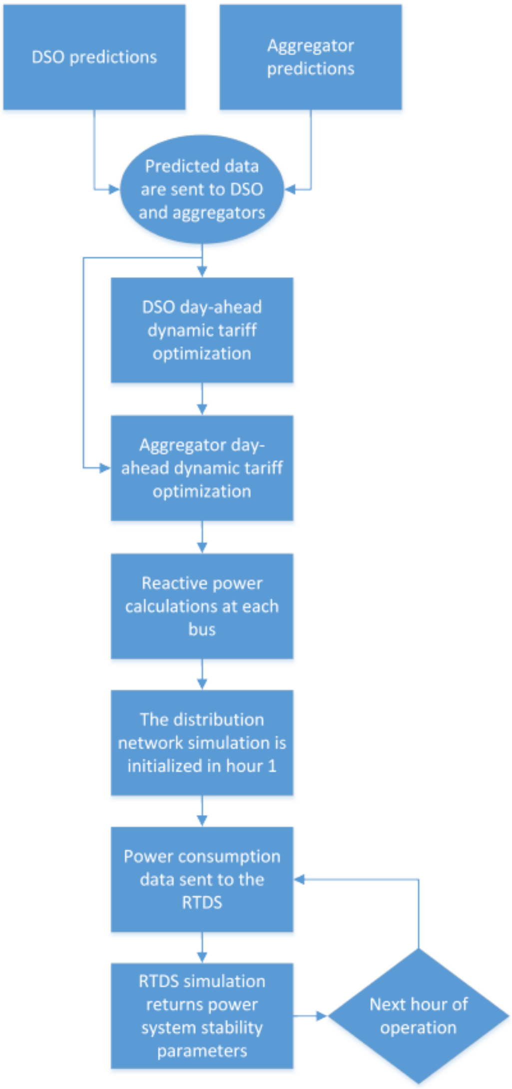

Figure 2 Flowchart of Testing Dynamic Tariff in RTDS

The MV distribution network of Rønne was implemented in the RTDS. The diagram of the distribution network is shown in Figure 3.

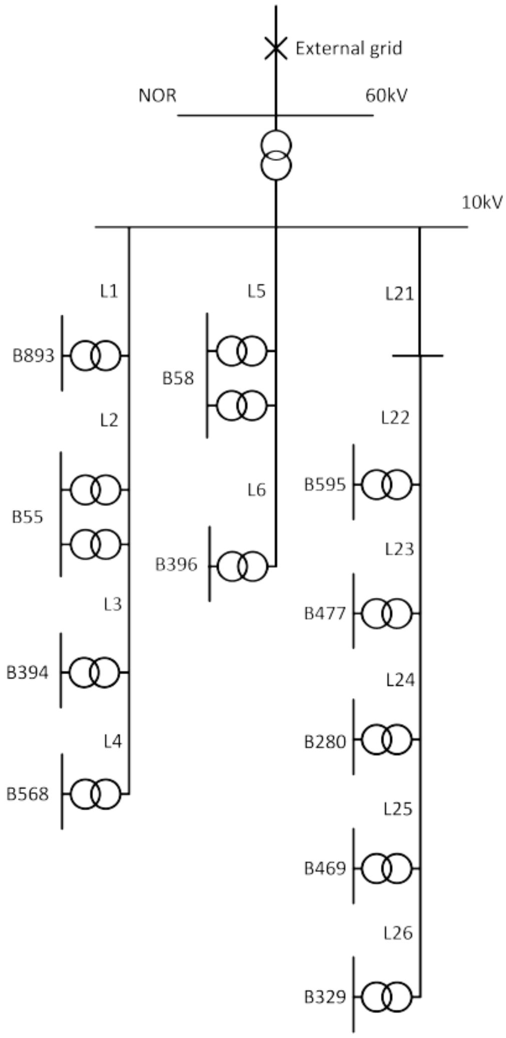

Figure 3 Diagram of Ronne Distribution Network

It is assumed that the penetration level of DERs is 75%. The currents of lines and limits are shown in Figure 4. It is shown that the DT cannot mitigate all the congestion and the line limits are exceeded due to the high reactive current. Therefore, it is important to improve the dynamic tariff for real implementation. One solution is to use the AC OPF to calculate the dynamic tariff. It can reflect the reactive current. Another option is to reserve a capacity margin to accommodate the inaccuracy of the dynamic tariff.

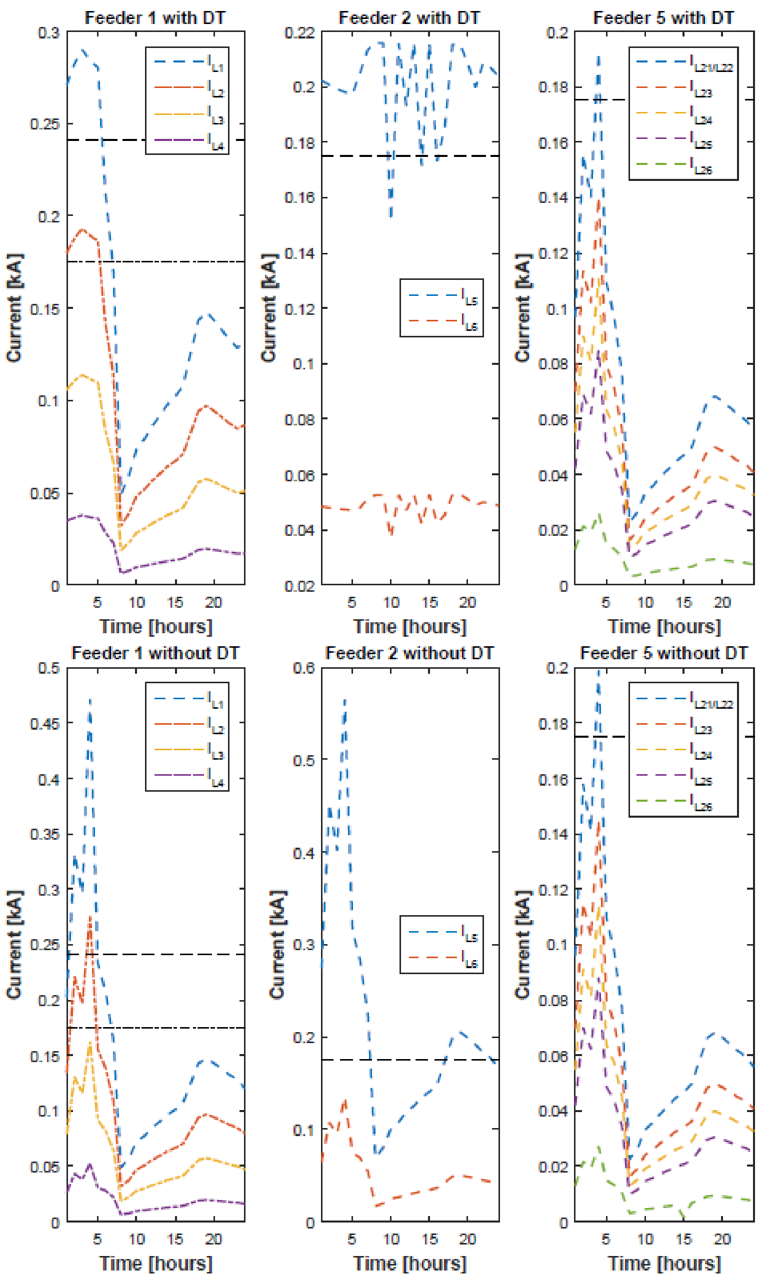

Figure 4 Line current of all transmission lines in the distribution network with a penetration level of 75% DERs

1.5.2 MPC-Based Coordinated Voltage Regulation for Distribution Networks With Distributed Generation and Energy Storage System

A centralized coordinated voltage control scheme is design based on the MPC to regulate the voltages in distribution networks with high penetration of DG and ESS. In this scheme, the active and reactive power of DG units, and charging/discharging power of ESS units are optimally coordinated. Moreover, the expected actions of OLTC are considered in the optimization problem. Compared with the existing work, the main advantages of proposed scheme are summarized as follows:

- The voltage regulation capabilities of DG units, ESS units and OLTC with different response time are fully utilized and optimally coordinated.
- The impact of OLTC actions on voltage is considered to mitigate the possible cluttering caused by the hunting between the DG/ESS units and OLTC.
- A modified clustering-based approach is proposed to better select the monitored (critical) buses in the networks.

- Two different control modes (preventive mode/corrective mode) are designed to coordinate the maximum energy usage and voltage regulation issue according to the operating conditions.

The control diagram of the proposed MPC based centralized coordinated voltage control scheme is shown in Figure 5.

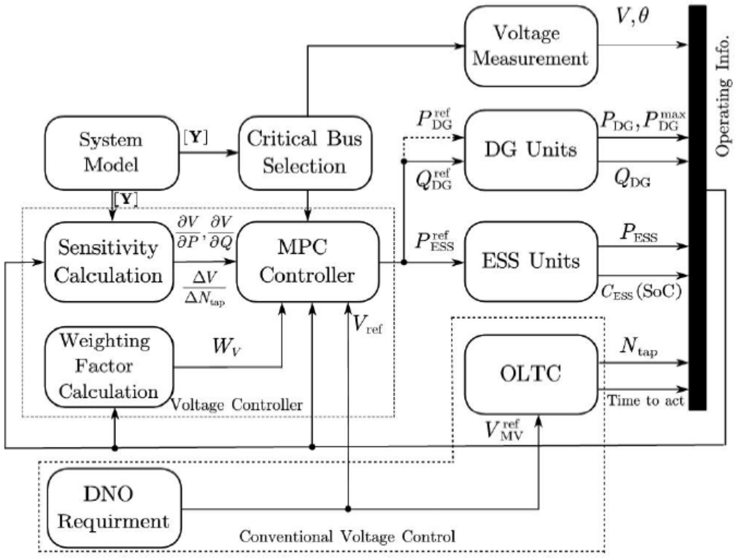

Figure 5 Control Diagram of MPC-Based Coordinated Voltage Regulation

The performance of the proposed MPC-based coordinated voltage control scheme is tested in a modified Finnish distribution network consisting of two 20 kV feeders which is shown in Figure 6. Two operation scenarios are considered in the simulation. Firstly, the control performance under normal operation only considering the fluctuation of DG power outputs and network load is tested. Secondly, the operation with large disturbances induced by the external grid is considered.

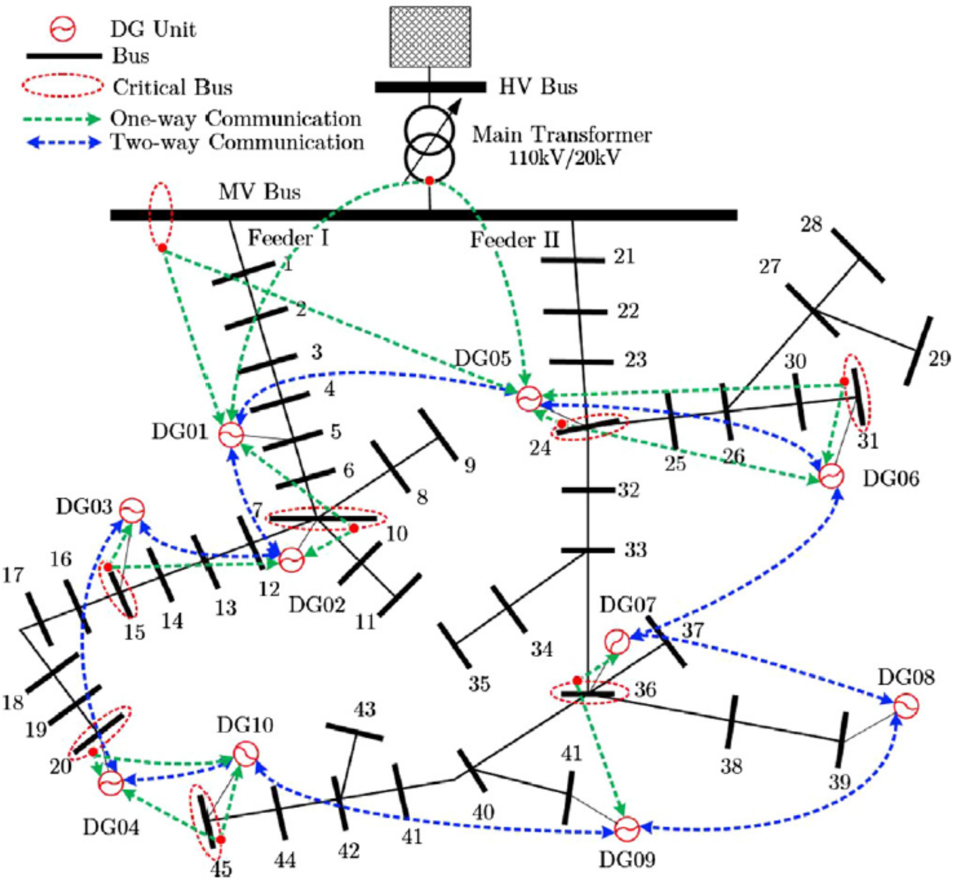

Figure 6 Network Topology of Test System

During normal operation, the control performance of the MPC-based coordinated voltage control method under normal operation is examined and compared with the conventional local power factor control (PFC) and the one-step optimization based optimal control (OPC). For the local PFC control, each DG unit operates with constant power factor, i.e., $Q = P\tan\psi$ where ψ is the power factor angle. To prevent the overvoltage issue, all DG units operate with the constant lagging power factor and $\cos\psi$ = 0:95 is considered in this study. For the OPC, the control period is also set as 2 s and it also has two same control modes with the MPC. Moreover, to illustrate the impact of the ESS in voltage regulation problem, the results of MPC without ESS are obtained for a comparison. The total simulation time is 1000 s. The simulation results are shown in Figure 7 - Figure 9.

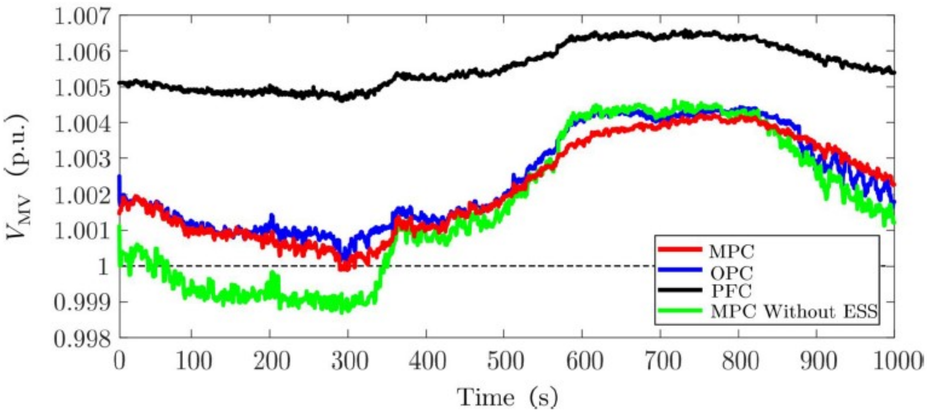

Figure 7 Voltage of MV Side Bust of Main Transformer

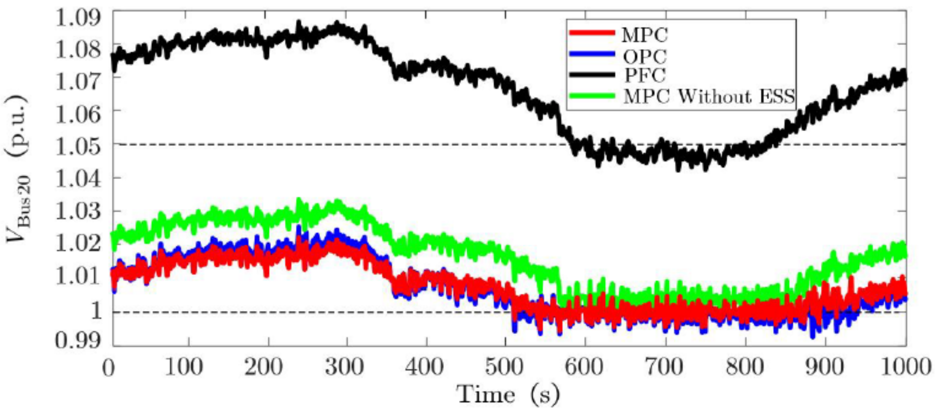

Figure 8 Voltage of Bus 20

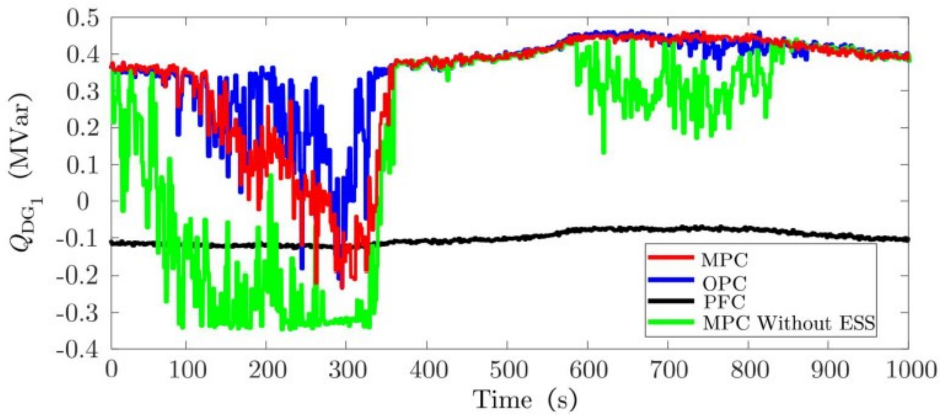

Figure 9 Reactive Power Output of DG01

As shown in Figure 7 and Figure 8, the MPC and OPC can both effectively regulate the voltages with small deviations and fluctuations. The fluctuation is mainly caused by the

active power variations of DG units. Comparatively, the MPC performs better than the OPC. The PFC fails to regulate the voltage at the end of the feeder (VBus20) within the feasible range. Moreover, introducing the ESS into voltage regulation can better regulate the voltages with smaller deviations and fluctuations.
It can be seen from Figure 9, compared with other methods, the MPC can better smooth the reactive power outputs of DG units. If the ESS is not included, the reactive power outputs of DG units may reach their limits, which may cause inadequate reactive power reserve under large-disturbance conditions. In other words, the ESS can alleviate the reactive power burdens of DG units.

To demonstrate the control performance during large-disturbance conditions, the network is affected by a large disturbance in the external grid, namely a sudden voltage increase of 0:1 p.u. at the slack bus (t = 50 s), which causes all bus voltages increase in the distribution network. Figure 10 shows the tap changes of the OLTC transformer. Figure 11 shows the voltage at Bus36. As can be seen, both of the OPC and MPC can better recover the voltage. Compared with the OPC, the MPC can make the voltage recover much faster and smoother due to the prediction mechanism and better coordination with the OLTC. The PFC shows limited voltage control capability.

The coordination between the OLTC (discrete and slow response) and DG/ESS units (continuous and fast response capability) can be explained as follows. For instance, at the control point of t = 74 s, since the DNO knows that there will be a tap change occuring at t = 74 s (actually, the tap action signal is triggered at t = 69 s but there is a mechanic time delay of 5 s), the DNO considers the potential tap change when optimizing the outputs of DG and ESS units. Thus, from Figure 11, it can be observed that, after the tap change at t = 74 s, the voltage fast recovers close to 1:0 p.u..

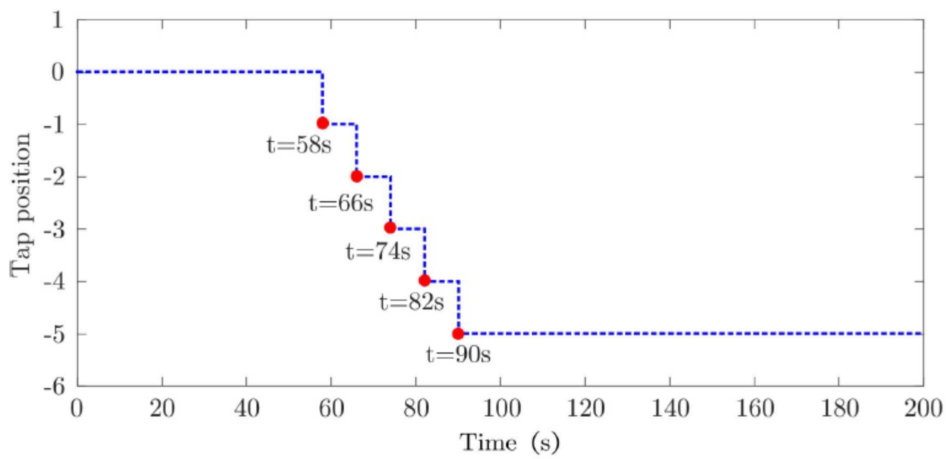

Figure 10 Tap Position

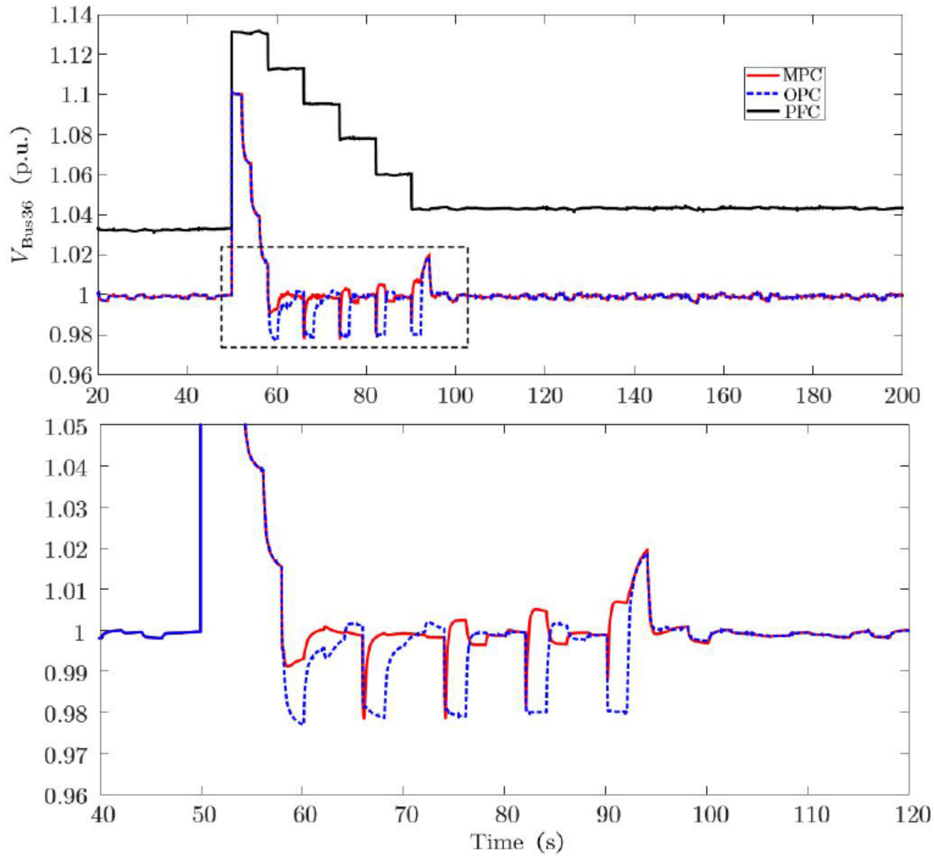

Figure 11 Voltage of Bus 36

To further illustrate the impact of active power curtailment of DG units on voltage regulation, the simulation results of the MPC with and without considering active power curtailment are compared. As can be seen from Figure 12, the voltage at Bus36 recovers much faster and smoother when considering the necessary active power curtailment of DG units, implying that the active power curtailment can significantly improve the voltage regulation capability during the large-disturbance conditions. There are sudden voltage fluctuations from t = 92 s to t = 94 s when considering the active power curtailment. It is because at t = 92 s the controller detects the voltages have recovered within the feasible range and thus the controller switches from the corrective mode to the preventive mode where the control objectives are different.

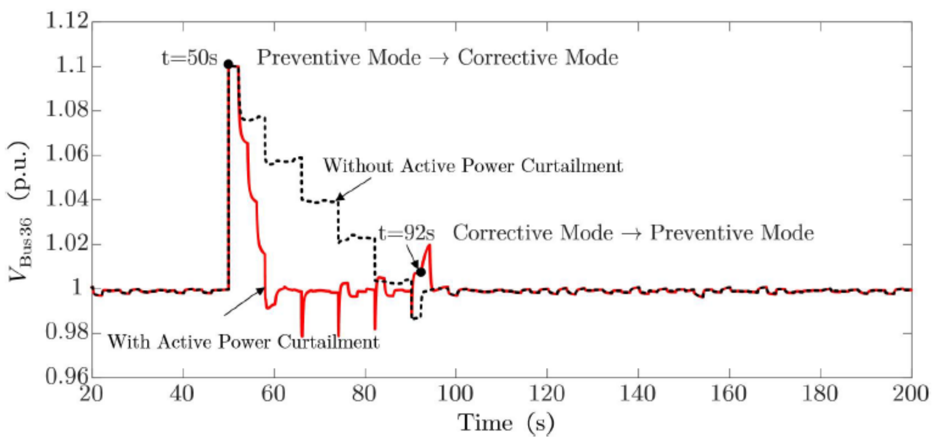

Figure 12 Voltage of Bust 36 under MPC with and without Active Power Curtailment

1.5.3 2 Distributed Voltage Regulation of Smart Distribution Networks: Consensus-Based Information Synchronization and Distributed Model Predictive Control Scheme

A distributed voltage control (DVC) scheme for smart distribution networks with high penetration of inverter-based DGs is proposed to better regulate the voltage across the network. The proposed scheme includes two important parts: (1) distributed information synchronization (DIS) framework and (2) distributed MPC (DMPC) based voltage control scheme. Compared with the existing works, the main contributions of this paper are threefold.

- A consensus-based DIS framework is proposed in this paper to synchronize the information including measured critical bus voltages and expected OLTC actions.
- The concept of DMPC is firstly used in voltage regulation of smart distribution networks with DGs, in which each DG unit only exchanges information with immediate neighboring DG units. Based on multi-step optimization, the proposed controller can smoothen system dynamics from the current state to the targeted state.
- The coordination between the OLTC with the distributed voltage control is addressed in this paper. The expected OLTC actions will be considered in the MPC formulation of each DG to avoid the mutual interaction with the OLTC.

The control diagram of the distributed voltage regulation of smart distribution networks is shown in Figure 13.

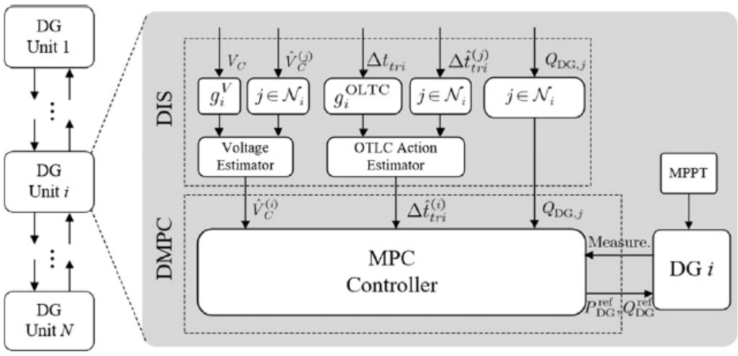

Figure 13 Control Diagram of Distributed Voltage Regulation of Smart Distribution Networks

The control performance of the proposed DVC (DMPC) under normal operation is presented and compared with the conventional local constant power factor control (PFC) and centralized MPC (CMPC). Considering the negligible communication delay and solution time of the centralized control methods, the control period of the CMPC is designed as 2s. Dynamic voltage profiles of Feeder I are shown in Figure 14. As can be seen from Figure 14(a), the local PFC fails to regulate the voltages within the predefined range of [0.95, 1.05]p. u.. However, the CMPC and DMPC can both effectively regulate the voltages within the range of [0.98, 1.02] p.u., implying the CMPC and DMPC have the similar control performances under normal operation. Moreover, the results can verify that the network voltage profile can be well regulated only based on several monitored voltage bus instead of all bus voltage measurements and feedback in the network. This would be helpful to reduce the communication and computation burdens of the system.

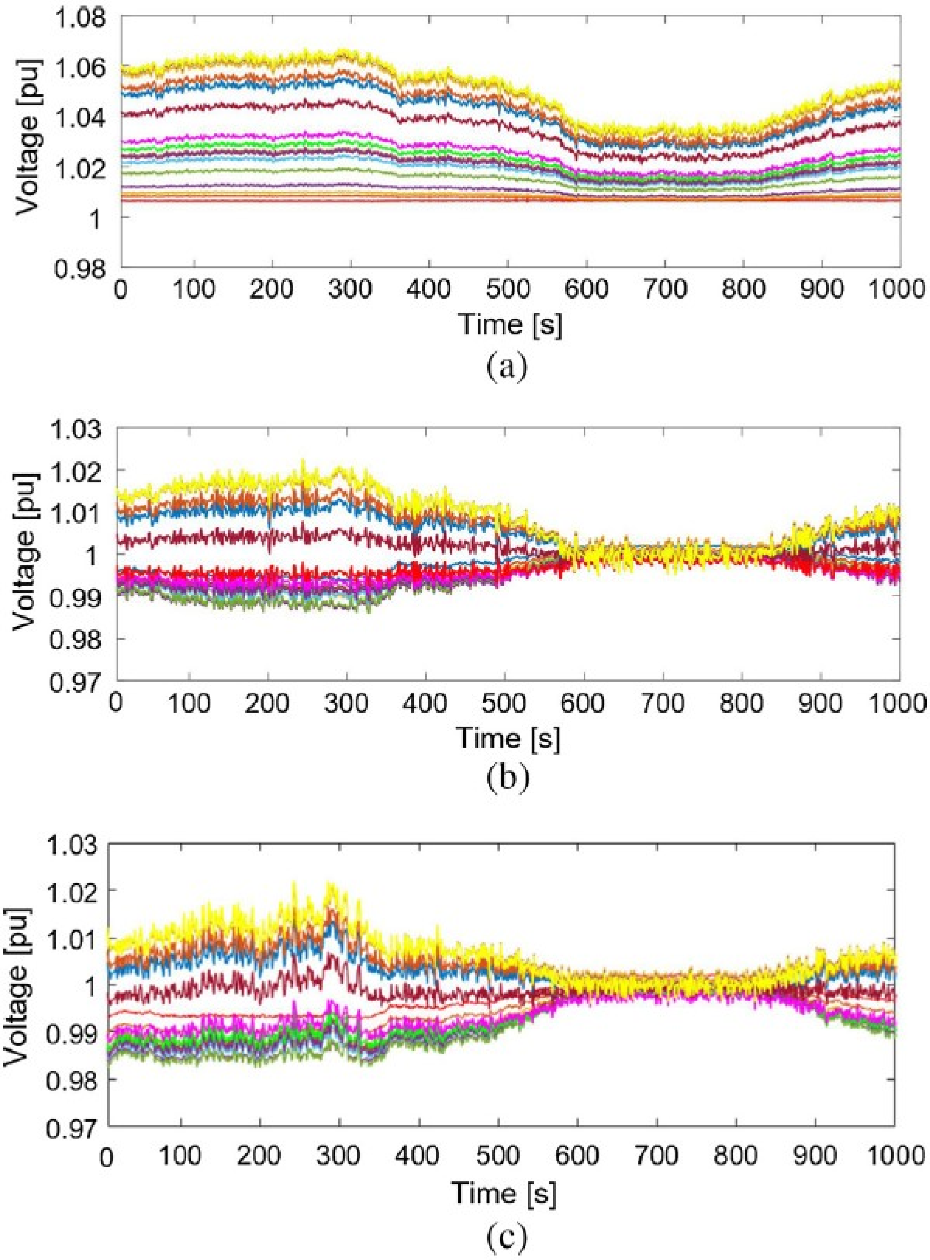

Figure 14 Voltage profile of Feeder I with the different control schemes (Different colors represent different bus voltages). (a) PFC, (b) CMPC, and (c) DMPC.

The control performance under large disturbances in the external grid is examined and compared with the PFC, CMPC and the conventional one-step optimization-based distributed optimal control (DOPC) without prediction mechanism, of which the control period is designed as 0.5s. At t = 50s, the distribution network is affected by a significant disturbance in the external grid, namely a sudden step increase of slack bus voltage (at the HV side of the main transformer).

The voltage performances under the emergency operation are illustrated in Figure 15 and Figure 16. Firstly, as can be seen from Figure 15, after the disturbance at t = 50s, the network voltages violate the predefined range and go beyond 1.1p. u.. Then, the OLTC and DVC can cooperatively correct the severe voltage deviations within the feasible range [0.98, 1.02] p.u. until t = 90s. As shown in Figure 16, the optimal control methods, i.e., the CMPC, DOPC and DMPC, can effectively accelerate the voltage recovery. Comparably, the DMPC can help voltages recover much faster.

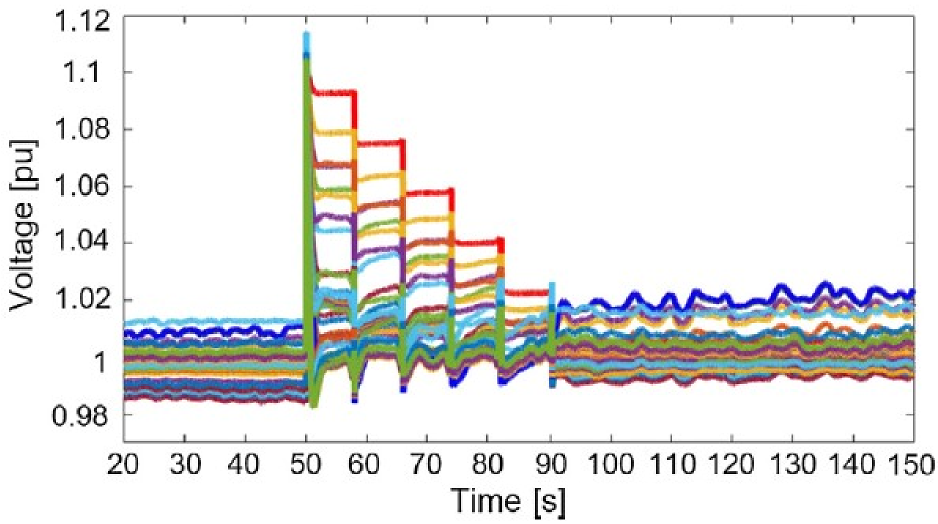

Figure 15 Voltage profile across the network with the DMPC

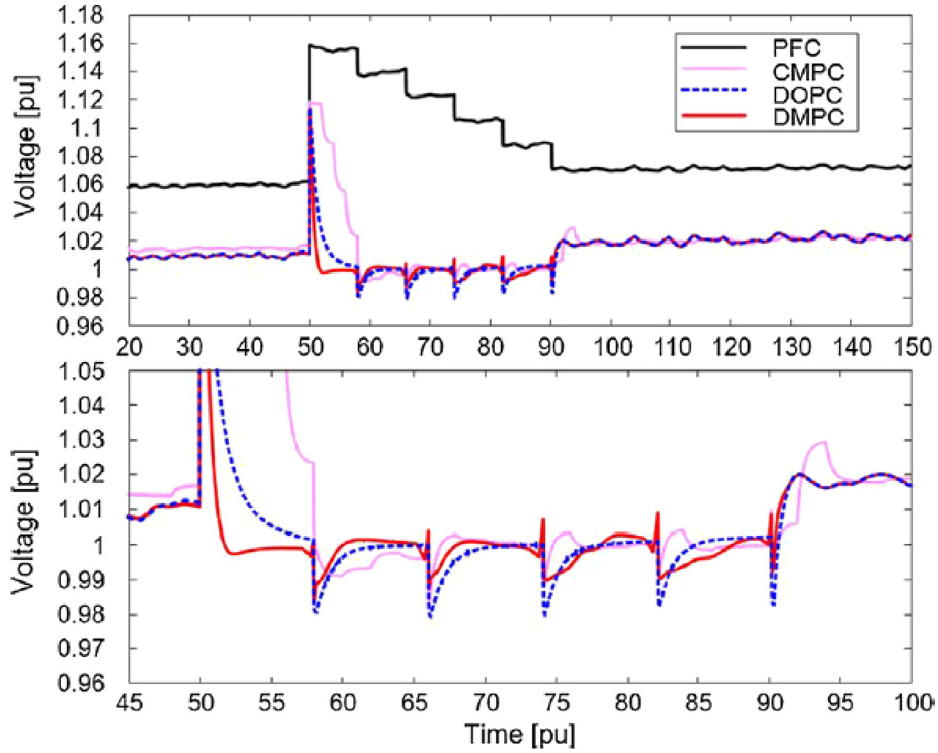

Figure 16 Comparison of voltages of Bus 20 under emergency operation with the PFC, CMPC, DOPC and DMPC

1.5.4 Double-Time-Scale Coordinated Voltage Control in Active Distribution Networks Based on MPC

A double-time-scale coordinated voltage control scheme is proposed for distribution networks with distributed generators (DGs) based on Model Predictive Control (MPC) to regulate the voltage profile across a network. The slow-timescale control (STC) scheme is designed to correct the long-term voltage deviations while reducing the number of actions of the on-load tap changer (OLTC), step voltage regulators (SVRs) and capacitor banks (CBs). The MPC problem is formulated as a mixed-integer quadratic programming (MIQP). A tailored exaction solution method based on the Branch-and-Bound (B&B) algorithm embedded with an Alternating Direction Method of Multipliers (ADMM)-based QP solver is developed to efficiently solve the MIQP problem. In the fast-time-scale control (FTC), the active and reactive power outputs of DGs are optimally coordinated to handle the fast voltage fluctuations as well as capture more renewable energy. An efficient analytical sensitivity calculation method is used to update the voltage sensitivities online. The control diagram is shown in Figure 17.

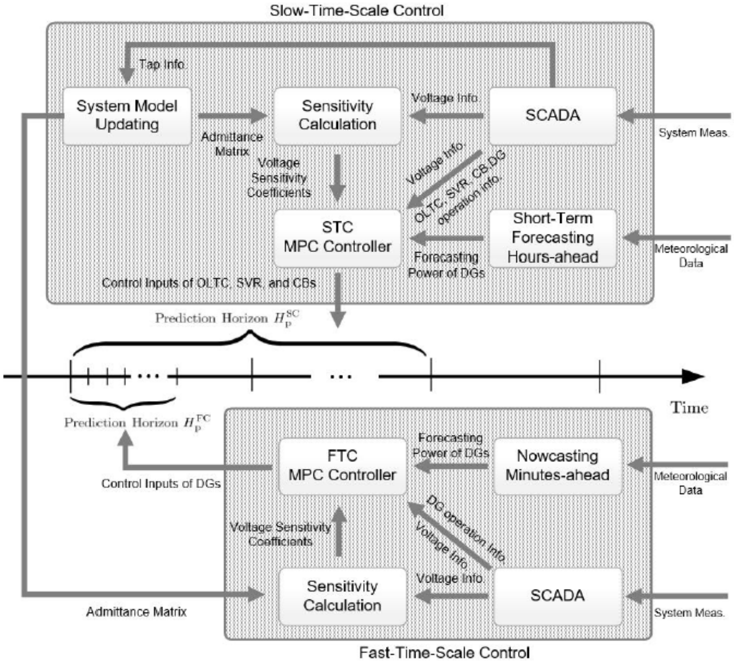

Figure 17 Control Diagram of Double-Time-Scale Coordinated Voltage Control

A modified Italian 20kV distribution network with four feeders and a total of 54 buses is used to demonstrate the effectiveness of the proposed double-time-scale coordinated voltage control.

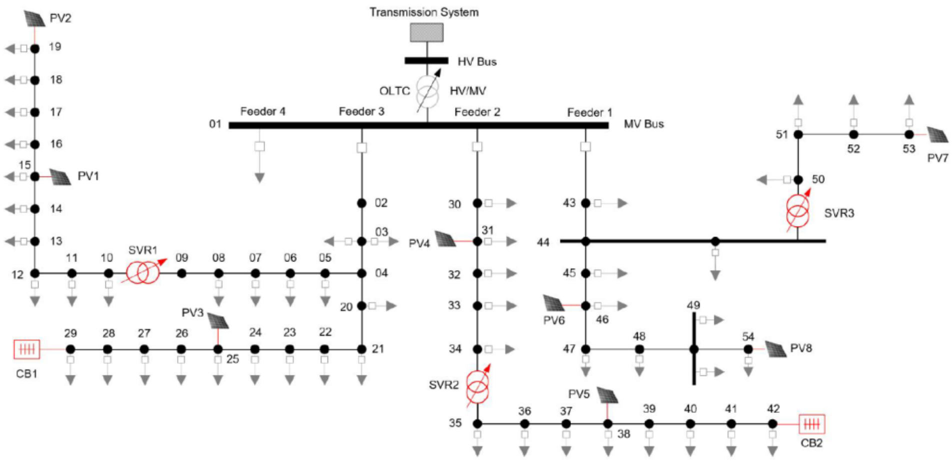

Figure 18 Configuration and topology of the test system

In Figure 19, the voltage profile (obtained by the AC power flow calculation) across the network with the proposed controller is compared with profiles without control and only with the STC. Figure 20 presents the reactive power outputs of DGs. Without any control (OLTC is set as nOLTCtap = 0), the voltage profile is much lower, with the most severe under-voltage occur during 18:00–20:00, approaching 0.86 p.u. (see Figure 19 (a)). If the lowest voltage is corrected to 0.95 p.u. (see Figure 19 (b), nOLTCtap = 5), the over-voltage will occur during 10:00–16:00, as the PV outputs are very high. It can be observed that the proposed control scheme can effectively regulate the voltage within the feasible range of 0.99–1.01 p.u.. By comparison, as shown in Figure 19(a), the voltages without control significantly fluctuate along with the fluctuations of load and PV outputs. During 18:00–20:00, several bus voltages are even lower than 0.9 p.u., indicating the severe voltage deviations. As shown in Figure 19(c), if only with the help of the STC, all bus voltages can also be effectively regulated within the range of 0.95–1.05 p.u., relying on the tap changers and CBs.

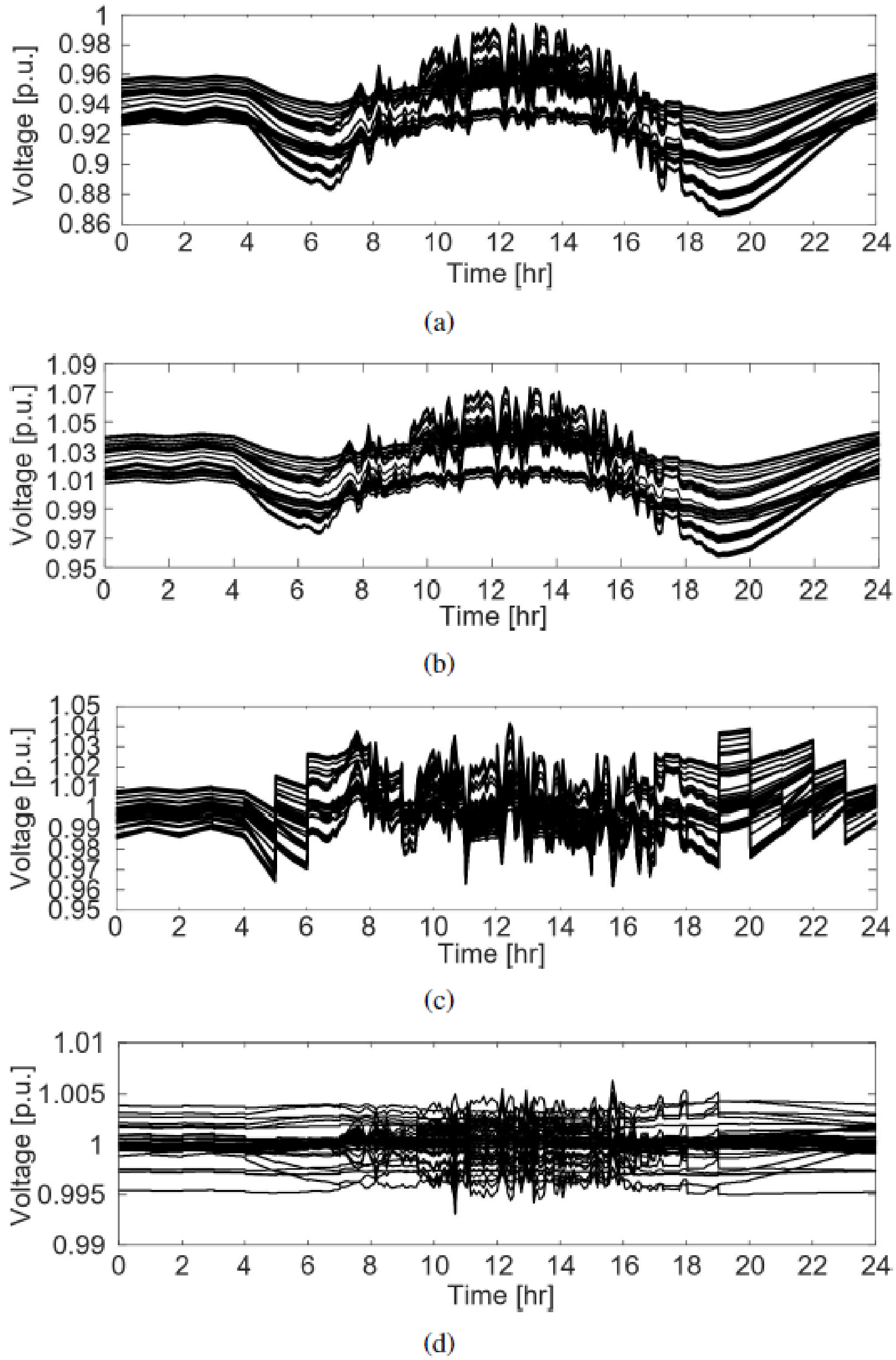

Figure 19 Voltage profile only with (a) no real-time control (nOLTCtap = 0), (b) no real-time control (nOLTCtap = 5), (c) the STC and (d) the proposed doubles-time-scale control scheme

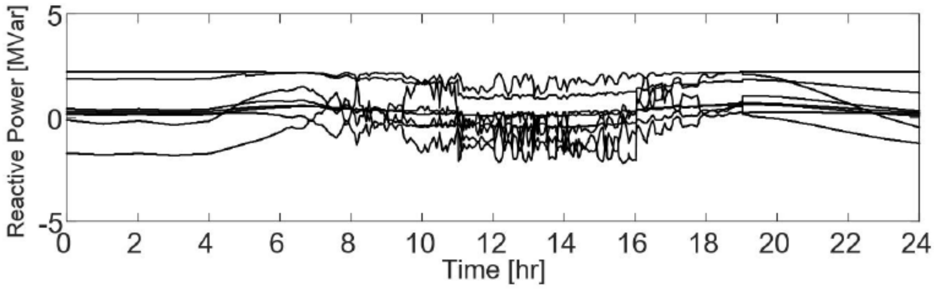

Figure 20 Reactive power outputs of DGs.

Dissemination

The project results were disseminated through scientific articles and master thesis. The results were published as 1 conference paper, 3 journal papers and 1 master thesis.

1 T. B. Rasmussen, Q. Wu, and S. Huang, "Real time emulation of dynamic tariff for congestion management in distribution networks," in Proc. ACEPT 2016.
https://ieeexplore.ieee.org/document/7811518
2 Y. Guo, Q. Wu*, H. Gao, and F. Shen, "Distributed Voltage Regulation of Smart Distribution Networks: Consensus-Based Information Synchronization and Distributed Model Predictive Control Scheme," *International Journal of Electrical Power and Energy Systems*, Vol. 111, pp. 58-65, Oct. 2019.
https://www.sciencedirect.com/science/article/pii/S0142061518330977
3 Y. Guo, Q. Wu*, H. Gao, X. Chen, J. Østergaard, "MPC based coordinated voltage regulation for distribution networks with distributed generation and energy storage system," *IEEE Transactions on Sustainable Energy, in press.*
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8463580
4 Y. Guo, Q. Wu*, H. Gao, S. Huang, B. Zhou, and C. Li, "Double-Time-Scale Coordinated Voltage Control in Active Distribution Networks Based on MPC," *IEEE Transactions on Sustainable Energy, in press.*
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8598889
5 Theis Bo Rasmussen, Real Time Emulation of Dynamic Tariff, Master thesis, 2016.

1.6 Utilization of project results

The dynamic tariff based on distribution locational marginal prices (DLMPs) is a very useful tool for distribution system operators to solve congestion in distribution systems with large scale integration of distributed energy resources (DERs) such as PV units, electric vehicles, heat pumps, ect. Quite many utility companies are looking into the possibility of implementing dynamic tariff to solve congestion.
The optimal voltage control methods developed in this project can maintain good voltages in distribution networks with DERs. They can also be used by utility companies to maintain secure operation.
The project partner is a university and do not plan to utilize the methods commercially.

1.7 Project conclusion and perspective

The dynamic tariff is effective for congestion management of distribution networks with high penetration of DERs in most cases. However, it should be improved either considering using AC OPF to calculate the dynamic tariffs or allocate a certain margin to deal with the inaccuracy of the DC OPF calculation.

The voltages in distribution networks with DERs can be maintained within the secure range by regulating the slow and fast var/voltage control devices. The distributed control scheme can also improve the privacy protection.

It will be nice to test both the dynamic tariff and optimal voltage control in the field and get them implemented in the real operation.

Annex
Relevant links

1 T. B. Rasmussen, Q. Wu, and S. Huang, "Real time emulation of dynamic tariff for congestion management in distribution networks," in Proc. ACEPT 2016.
https://ieeexplore.ieee.org/document/7811518

2 Y. Guo, Q. Wu*, H. Gao, and F. Shen, "Distributed Voltage Regulation of Smart Distribution Networks: Consensus-Based Information Synchronization and Distributed Model Predictive Control Scheme," *International Journal of Electrical Power and Energy Systems*, Vol. 111, pp. 58-65, Oct. 2019.
https://www.sciencedirect.com/science/article/pii/S0142061518330977
3 Y. Guo, Q. Wu*, H. Gao, X. Chen, J. Østergaard, "MPC based coordinated voltage regulation for distribution networks with distributed generation and energy storage system," *IEEE Transactions on Sustainable Energy, in press.*
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8463580
4 Y. Guo, Q. Wu*, H. Gao, S. Huang, B. Zhou, and C. Li, "Double-Time-Scale Coordinated Voltage Control in Active Distribution Networks Based on MPC," *IEEE Transactions on Sustainable Energy, in press.*
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8598889