LABORATORY EVALUATION OF A DETERMINISTIC OPTIMAL POWER FLOW ALGORITHM USING POWER HARDWARE IN THE LOOP

Timur SAYFUTDINOV
Skoltech – Russian Federation
timur.sayfutdinov@skolkovotech.ru

Pádraig LYONS
Newcastle University – United Kingdom
Padraig.Lyons@newcastle.ac.uk

Martin FEENEY
Newcastle University – United Kingdom
martin.feeney@newcastle.ac.uk

ABSTRACT

The evaluation of a centralized voltage optimization algorithm from a perspective of future distribution network with high penetrations of distributed generation using a laboratory featuring Power Hardware-in-the-Loop (PHiL) technology is presented in this paper. This work will enable practical evaluation of state-of-the-art voltage control equipment in future challenging network scenarios using PHiL equipped laboratory.

INTRODUCTION

Smart grid technologies can provide flexible and economic operational solutions for distribution networks. These technologies can enable operation of voltage control devices cooperatively and could mitigate voltage problems in future networks [1, 2]. Information and communication technologies are key enablers for these advanced voltage control schemes. Besides smart grid devices, such as Distributed Generation (DG) and Electrical Energy Storage (EES), conventional voltage control devices can also be integrated in advanced voltage control scheme effectively. The primary objective of any voltage control approach is to maintain network voltages within statutory limits. However, it is possible to embed various additional objectives, including operation cost reduction and efficient energy management into these schemes [2].

Previously, load changes have been the principal cause of voltage deviation in conventional distribution networks. In future networks, load is expected to increase due to the anticipated electrification of transport and heat [3]. These developments coupled with the connection of large quantities of renewables based DGs will result in more challenging conditions for the operation of future networks.

In conventional voltage control architectures, control devices are operated on the basis of local measurements only, and are coordinated passively [3]. It has been shown that advanced voltage control schemes will be required to solve future voltage problems, where conventional approaches may struggle to provide adequate or economic solutions [4]. Various advanced architectures and algorithms have been proposed for voltage control schemes previously [1]. Generally, these architectures can be categorized as centralized or distributed control architectures, both of which could potentially provide solutions for these problems [1].

The objective of this work is to evaluate centralized voltage optimization algorithms from a perspective of future distribution network with high penetrations of DGs using smart grid laboratory, featuring Power Hardware-in-the-Loop (PHiL) technology. This is achieved by integrating real-time network simulation, a Low Voltage (LV) network, smart grid control systems and a voltage optimization scheme within the laboratory using high-speed digital links and a flexible three-phase inverter. This approach enables practical evaluation of voltage control systems, featuring state-of-the-art next generation voltage control devices in future challenging network scenarios.

PROBLEM FORMULATION

This work considers snapshot control problem formulation for searching the Optimal Power Flow (OPF) solution to minimize network losses within distribution networks. The objective function for this OPF problem is a sum of the real power losses on all the distribution network branches (1).

$$f_{Loss} = \sum_{n=1}^{N_{branch}} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}) \qquad (1)$$

$$\underline{V_i}\sum_{j=1}^{N_{busbar}} \underline{Y_{ij}V_j} = P_i - jQ_i, i = 1,...,N_{busbar} \qquad (2)$$

$$u_i^{\min} \le u_i \le u_i^{\max}, i = 1,...,N_u \qquad (3)$$

$$f_{penalty} = \sum_{i=1}^{n} \begin{cases} s_i\left(x_i - x_i^{\min}\right)^2, x_i < x_i^{\min} \\ 0, x_i^{\min} \le x_i \le x_i^{\max} \\ s_i\left(x_i^{\max} - x_i\right)^2, x_i > x_i^{\max} \end{cases} \qquad (4)$$

Equality constraints (2) are used to emulate the relationship between the network voltages and the net injected power at different busbars. Inequality constraints (3) specify limits of control and state variables.

To keep busbars' voltages within statutory limits a penalty function is introduced (4). In a similar way, another penalty function is used to reduce EES charge/discharge cycles as this has an effect on the devices lifetime.

Oriented Discrete Coordinate Descent Method (ODCDM) was chosen for the voltage optimization algorithm, as it has high computational speed, high reliability, and excellent convergence properties [5]. In [6], ODCDM for distribution network voltage control was first used. On Load Tap Changing (OLTC) transformers and Mechanically Switched Capacitor banks (MSCs) were operated cooperatively to maintain voltages within the statuary limits and to minimize the network losses. In [3], authors use continuous voltage control devices, such as EESs and DGs, as well as discrete control devices, such as OLTC transformers and MSCs. This mix of discrete and continuous devices makes it a mixed integer nonlinear programming problem. To apply it for ODCDM one of the possible solutions is to discretize continuous variables with a certain step size, as it was adopted in [7].

CASE STUDY NETWORK AND PHIL SETUP

A case study network in this work was based on an existing distribution network in the northeast of England and owned by Northern Powergrid. This model is based on validated models that have been previously developed for the CLNR project programme [7]. For this study one 20 kV branch is considered. A single line diagram of the case study network is illustrated in Fig. 1.

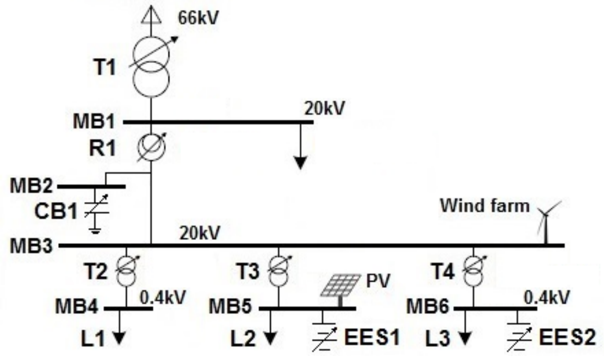

Fig. 1 Case study network

The case study network contains five OLTC transformers, one MSC and two EESs. The operating range of OLTC transformers T1-T4 are (91; 109) % with 1.5% step size and (87.5; 100) % for R1 with 1.25% step size. The operating range of MSC is (-4; 0) MVAr with 0.5MVAr step size. The operating range of EES1 is (-0.05; 0.05) MW and (-0.04; 0.04) MVAr. The operating range of EES2 is (-0.1; 0.1) MW and (-0.08; 0.08) MVAr. Both EES units have been discretized to have 0.01 MW/MVAr step sizes.

In order to investigate a future distribution network scenario a wind farm and photovoltaic (PV) generation is added to the network. Generation profiles for wind farm and PV, based on real data from the CLNR project [7], were developed to investigate voltage control operation under credible extreme conditions that would move the network towards its operational limits. Load data measured from the real distribution network was implemented in the real-time simulations. Total energy consumption and generation within the distribution network are 69.6 MVAh and 68.2 MVAh respectively.

The diagram of the equipment used during this work is shown in Fig. 2. The laboratory setup contains a Real Time Simulator (RTS) supplied by OPAL-RT, a flexible three-phase inverter, LV busbar and Automatic Voltage Control relay (AVC). The validated distribution network model (Fig. 1) and voltage control algorithm are run in real-time in the RTS. Voltages from busbars within the real-time network model are sent from the RTS system to the three-phase inverter which is used to supply these voltages to the LV busbar within the laboratory.

When the AVC is integrated into the centralized voltage control scheme, its tap change function is controlled by the OPF based voltage control algorithm running in the RTS. The AVC in turn is controlling the tap-position of the OLTC transformer model in the RTS. In addition, if the AVC is not operating under centralized control it measures laboratory LV network voltage and performs the distributed voltage control functions.

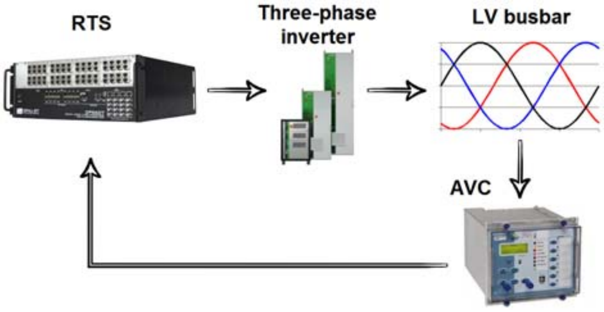

Fig. 2 Smart grid laboratory setup

Two 24 hours PHiL test runs were conducted to enable this laboratory based evaluation of centralized voltage control schemes. In the first test run existing conventional Time Delay (TD) based voltage control scheme was implemented. For the second test run a centralized voltage control scheme that was developed as part of this research was evaluated. The load and generation scenarios for both test runs were identical. These scenarios were developed to investigate the operation of future distribution networks under conditions near operational limits e.g. high winds, high level of solar radiation and heavy loads across the system.

ODCDM based voltage control is a centralized approach, which requires measurements or pseudo measurements (from a state-estimator) from all the busbars of the network and determines the most effective device to minimize network losses in real time.

TD based voltage control approach was used to provide a baseline level of operation to compare with the ODCDM approach. TD based voltage control is a distributed approach with no communication between devices. Thus, each voltage control device uses only local measurements to perform its operation. To avoid excessive mechanical switching operations in OLTC transformers and MSCs, time delays and dead bands are implemented. In general, equipment running at higher nominal voltages has shorter time delays and vice versa. EESs are controlled with PI-controllers in distributed voltage control scheme.

The dead band of EES operation for TD based voltage control is set to (95; 109) % of nominal value and (97; 107) % for the ODCDM scheme. In order to reduce EES use, all the other voltage control devices for both techniques are configured to maintain voltage level within tighter limits – (97; 105) % of nominal value.

As the voltage control problem can be non-convex ODCDM based systems may find local minimum rather than the global minimum of the objective functions depending on the Starting Point (SP) [3]. Therefore, there may be a number of different solutions for different SPs. The SP of each voltage control device was the same for both 24 hours PHiL test runs. The SP is specified for minimum active power losses at an initial time (00:00).

RESULTS

Distributed voltage control

Voltage profiles of LV busbars are shown in Fig. 3. It can be seen, that there are some periods of time during the 24 hour test run when the voltage magnitudes are outside the statutory limits.

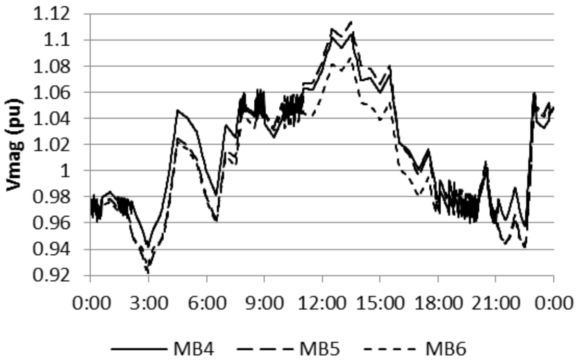

Fig. 3 Voltage profiles of LV busbars (TD)

Tap positions of the OLTC transformers controlled by distributed voltage controllers are shown in Fig. 4.

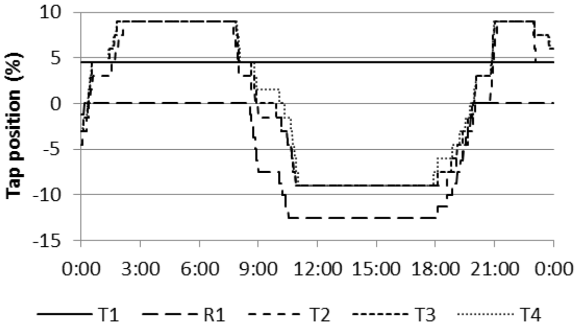

Fig. 4 Tap positions of OLTC transformers (TD)

The amount of reactive power injected into the network by the MSC during the test run is shown in Fig. 5.

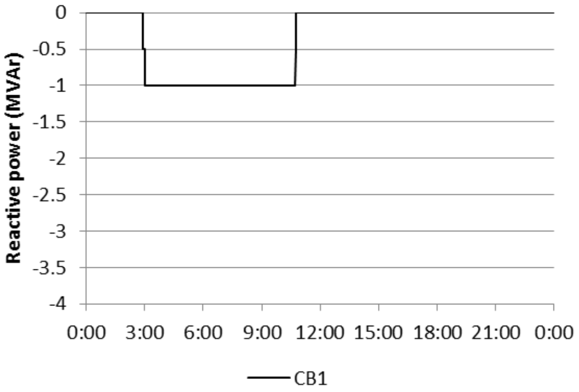

Fig. 5 Reactive power injected by MSC (TD)

The amount of active and reactive power injected or stored from the network by EESs is shown in Fig. 6.

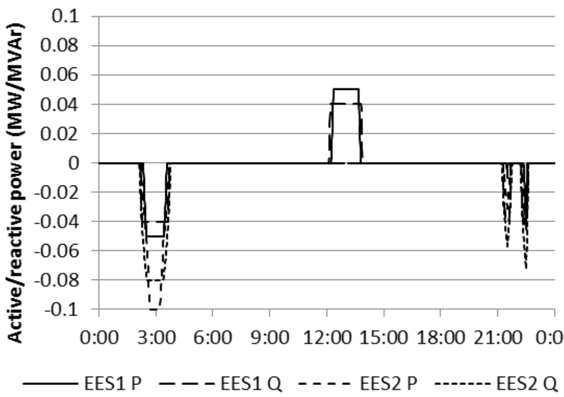

Fig. 6 Power injected/stored by EESs (TD)

As each voltage control device responds only to local events, some devices hit saturation limits and are unable to receive support from other voltage control devices in the network. Total active power losses within the distribution network during the test run were 12 MWh.

Centralized voltage control

Voltage profiles of LV busbars are presented in Fig. 7. The centralized voltage control scheme kept the voltage magnitude of the LV network busbars within statutory limits for the duration of the test run.

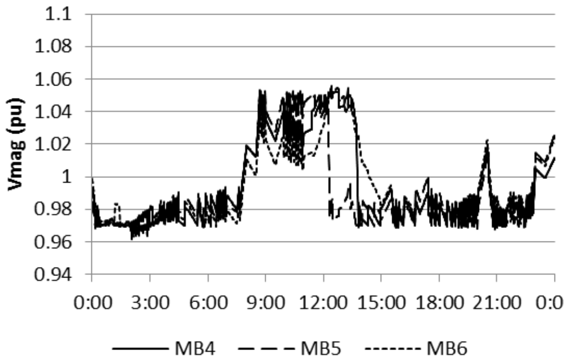

Fig. 7 Voltage profiles of LV busbars (ODCDM)

Tap positions of OLTC transformers during the second test run are shown in Fig. 8.

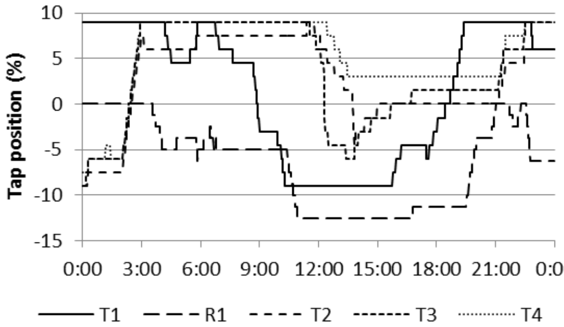

Fig. 8 Tap positions of OLTC transformers (ODCDM)

Fig. 9 presents the amount of reactive power injected by the MSC. Heavy load and sawtoothlike load profile resulted in multiple switch operations of the MSC in the beginning of the test run.

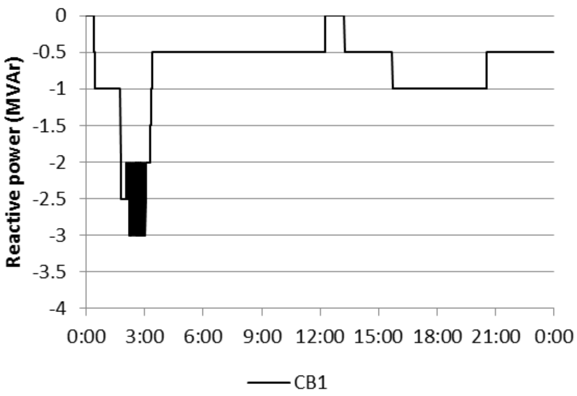

Fig. 9 Reactive power injected by MSC (ODCDM)

Fig. 10 presents the amount of power injected by EESs.

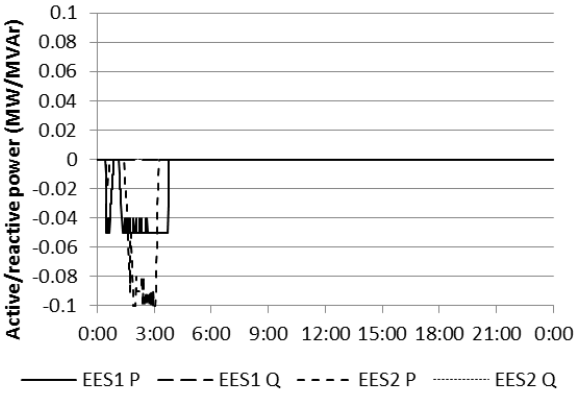

Fig. 10 Power injected by EESs (ODCDM)

All the voltage control devices are actively used by centralized, ODCDM based voltage control scheme. Even if one of the voltage control devices is saturated to deal with voltage problem, centralized controller requests another voltage control device to assist.

Total active power losses within the distribution network during the second test run were 9.3 MWh.

Comparison

Firstly, it can be noted from the processed data is that the advanced voltage control scheme had a greater capability to mitigate voltage problems, in comparison with the conventional, distributed voltage control scheme.

Secondly, ODCDM based voltage control scheme was able to reduce active power losses by 22.5% in comparison with the distributed voltage control scheme.

Furthermore, the centralized voltage control scheme has reduced EES charge/discharge cycles reducing its operation cost.

However comparing to the TD based voltage control scheme, ODCDM based system has a greater number of switching operations which are costly as well.

CONCLUSION

The capabilities of advanced voltage control schemes have been investigated in this paper using a laboratory test platform. To enable a sophisticated combination of voltage control hardware, laboratory hardware and real-time simulation systems were integrated to develop a test platform. The centralized voltage optimization algorithm, based on ODCDM, was implemented and evaluated using a 24 hours PHiL test run and the experimental results were compared with a similar 24 hours PHiL test run which utilized TD based voltage control scheme. The data and scenarios were developed using data from the UK's largest smart grid programme and were the same for both test runs to enable comparison.

The experimental results have shown that the advanced voltage control scheme was able to control the voltages in the future network scenario in contrast to the conventional TD based voltage control scheme which had a number of voltage excursions.

ACKNOWLEDGMENTS

The work was supported by The Ministry of Education and Science of Russian Federation, grant No. 14.615.21.0001, grant code: RFMEFI61514X0001.

REFERENCES

[1] T. Strasser, F. Andren, J. Kathan, C. Cecati, C. Buccella, P. Siano, *et al.*, 2014, "A Review of Architectures and Concepts for Intelligence in Future Electric Energy Systems," *Industrial Electronics, IEEE Transactions on,* vol. PP, 1-1.

[2] X. Fang, S. Misra, G. Xue, D. Yang, 2012, "Smart Grid – The New and Improved Power Grid: A Survey," *Communications Surveys & Tutorials, IEEE*, vol. 14, 944-980.

[3] W. Pengfei, 2015, "Evaluation of advanced voltage control algorithms for future smart distribution networks," PhD, School of Electrical and Electronic Engineering, Newcastle University, Newcastle, UK.

[4] R. W. Uluski, 2010, "VVC in the Smart Grid era," *Power and Energy Society General Meeting, 2010 IEEE*, 1-7.

[5] S. Frank, I. Steponavice, S. Rebennack, 2012, "Optimal power flow: a bibliographic survey I," Energy Systems, vol. 3, 221-258.

[6] I. Roytelman, B. K. Wee, R. L. Lugtu, 1995, "Volt/var control algorithm for modern distribution management system," *Power Systems, IEEE Transactions on,* vol. 10, 1454-1460.

[7] J. Tianxiang, B. Simon, L. Pádraig, W. Pengfei, Y. Jialiang, 2014, "CLNR Post Trial Analysis EES2 and EES3 GUS Powerflow Management," School of Electrical and Electronic Engineering, Newcastle University, Newcastle, UK.