Decentralized and Distributed Coordinated Voltage Control: Coordinated Control of DERs to Enhance LV Distribution Network Voltage Profile

1. Project Introduction

The penetration level of photovoltaic (PV) generation in power distribution network is increasing significantly in recent year. The voltage qualities of distribution network are threatened by the uncertainty of PV generation. While the reactive power provided by the interfacing inverters has becoming a potential solution for network voltage regulation.

In this project, a decentralized and distributed coordinated voltage control method based on reactive power of PV inverters is proposed in distribution networks. The proposed control approach comprises three level hierarchy: ramp-rate control (Level I), droop control (Level II), and distributed control (Level III). In Level I, a ramp-rate control is proposed to mitigate the network voltage fluctuations. While in Level II, a droop control is designed to mitigate the network voltage deviations. If the local compensation provided by Level I and II control is not enough to regulate the network voltage deviations within limits, the distributed control at Level III will respond and share the reactive power requirement to other inverters. The distributed control will determine the reactive power requirements of all available inverters autonomously, so that the network voltages are controlled within the required limits. The proposed control method can smooth the voltage profiles, restrain the voltage rise/drop problem, and coordinate all PV inverters in real-time when there is no feasible local solution.

Power hardware-in-the-loop (PHiL) experiment with realistic communications between inverters has been conducted to validate the performance of the proposed control method.

2. Methodology

The proposed control method contains three hierarchies and the operating voltage ranges of each level is shown in Fig.1. Level I control, i.e., the ramp-rate control, operates at all voltage ranges mitigating the fluctuations in network voltage. Level II control, i.e., the droop control, mitigates the deviations when the bus voltage is out of the desirable range $[V_{\%}, V^{\%}]$. Level III control, i.e., the distributed control, will be activated when the bus voltage is beyond the allowable range $[\underline{V}, \bar{V}]$. In the proposed voltage control method, the Level I and II control will operate with a faster rate based on local voltage measurement only. Level III control will operate with a slower rate based on communication speed between the participating inverters.

The overall structure of the the proposed control method is shown in Fig. 2. For a distribution network with *N* multiple PV inverters, there are *N* corresponding identical controllers for these PV inverters. The reactive power output of a PV inverter is the sum of the three levels' utilization ratios times the reactive power capacity of the PV inverter. The proposed control approach enables each PV inverter to participate in network voltage regulation fairly and in accordance to its available reactive power capacity. The details of individual control levels will be explained in the following sub-sections.

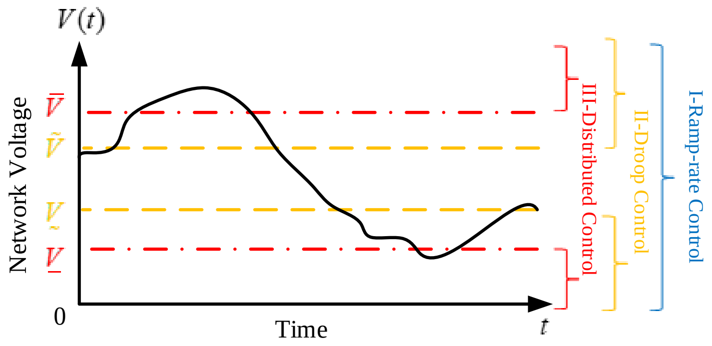

Fig. 1. The illustration of the proposed voltage control method.

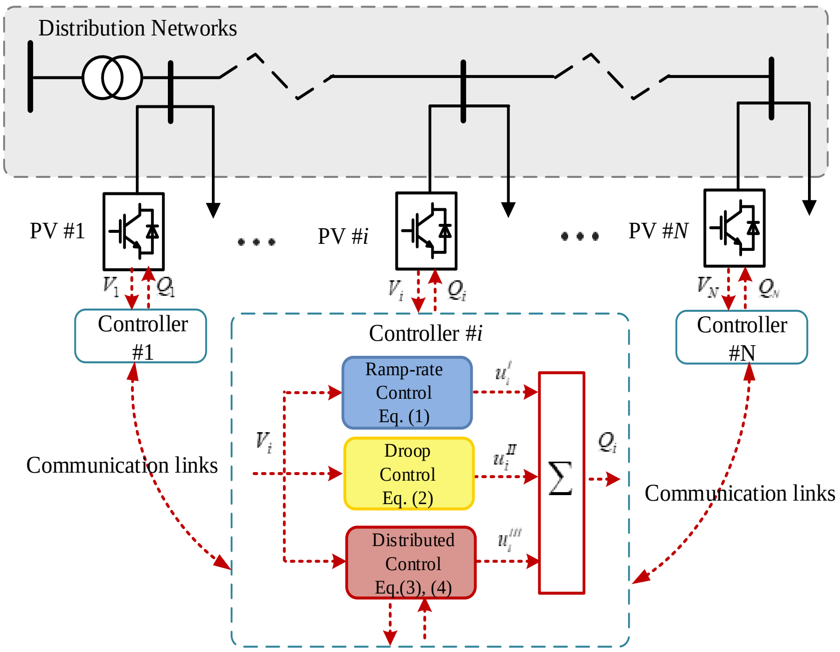

Fig. 2. The overall structure of the proposed voltage control method.

2.1. Level I: Ramp-rate Control

The utilization ratio of Level I control is represented as:

$$u_i^I(t) = K_i^I \left(V_i(t) - \frac{\sum_{j=t-\omega}^{t} V_i(j)}{T(t) - T(t-\omega)}\right) \tag{1}$$

where, ω is the length of the moving average window and K_i^I is the ramp-rate control gain.

2.2. Level II: Droop Control

The utilization ratio of Level II control is represented as:

$$u_i^{II}(t)=\begin{cases}K_i^{II}(V_i(t)-\overline{V}), & V_i(t)>\overline{V}\\ 0, & \underline{V}\le V_i(t)\le \overline{V}\\ K_i^{II}(V_i(t)-\underline{V}), & V_i(t)<\underline{V}\end{cases} \tag{2}$$

K_i^{II} is the droop gain of i^{th} PV inverter. $[\underline{V}, \overline{V}]$ represents the dead band for the droop control.

2.3. Level III: Distributed Control

The utilization ratio of Level III control is represented as:

$$e(t)=\begin{cases}K_i^{III}(V_i(t)-\overline{V}), & V_i>\overline{V}\\ 0, & \underline{V}\le V_i\le \overline{V}\\ K_i^{III}(V_i(t)-\underline{V}), & V_i<\underline{V}\end{cases} \tag{3}$$

$$\dot{u}_i^{III}(t)=G_i^{III}[\sum_{i=1}^{N}a_{ij}(u_j^{III}(t-\tau(t))-u_i^{III}(t))]+e(t) \tag{4}$$

where K_i^{III} and G_i^{III} are the distributed control gains. $\tau(t)$ is the time varying communication delay where $0\le\tau(t)\le\overline{\tau}$ with $\overline{\tau}$ being the tolerable communication delay upper bound.

3. Experimental Platform Set-up

In order to test the proposed control algorithm in a more realistic environment, PHIL experiment is conducted [1]. Fig. 3 shows the hardware-in-the-loop test platform in this project. The PV inverter and load demand at bus 5 are replacing with real laboratory equipment. A 15kVA inverter and a 40kW resistive load bank with a 90kVA interfacing converter is used, as shown in Fig. 3. The voltage and current signals between scaled up and down between the real-time simulation and the hardware equipment. For an increased accuracy of the PHIL implementation the time delay compensation technique presented in [2] has been used. The remaining components of the 7-bus distribution network are simulated in the real time digital simulator (RTDS).

The proposed control scheme has been developed for each PV inverter separately in RTDS, and the entire system is operated in real-time with a time step of 50us. Furthermore, all the communications required for the distributed control algorithm are implemented through a real communication network. Control signals are independently routed outside of the RTDS with GTNET cards, then into a communication emulator software and finally back into neighboring controllers in the RTDS. This allows for the evaluation of real dynamics introduced by the PV inverter and also analyzing the impact of realistic communication on the proposed control scheme.

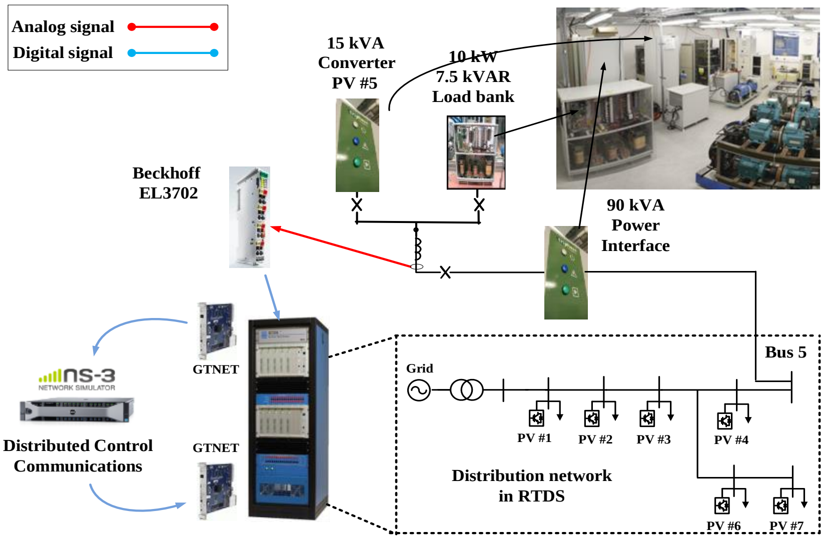

Fig. 3. Hardware-in-the-loop test platform.

4. Results and Discussions

4.1. Test Case 1: Voltage Drop with Step Load Change

In Test Case 1, the ability of the proposed control approach to mitigate sudden voltage drops due to step changes in load is tested. Such a situation would normally occur in the evening in distribution grids, when load demand is high but there is a lack of PV generation. As there is no PV production, all capacity of PV inverters can be utilized to supply reactive power for network voltage regulation. The communication delay in distributed control is not considered in Test Case 1. Three step changes in load are emulated, in terms of percentage representable as: (i) an increase from 35% to 65% at *t*=30s; (ii) a further increase from 65% to 100% at *t*=130s; and (iii) a decrease from 100% to 35% at *t*=230s.

The network voltage profiles and the corresponding PV inverters reactive power outputs have been shown in Fig. 4 and Fig. 5, respectively. As can be observed from Fig. 4, the network voltages are always regulated within $[\underline{V}, \bar{V}]$ in steady-state. The PHiL results reinforce the ability of the proposed control approach to: (i) mitigate voltage drop issues and (ii) work under step load changes.

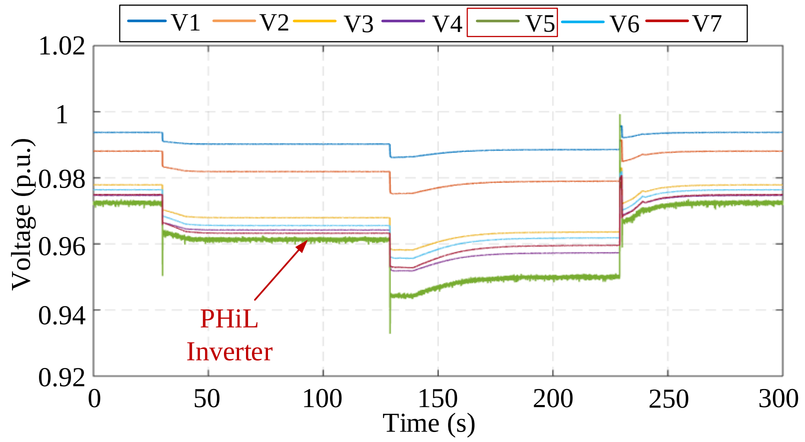

Fig. 4. Voltage profiles of the distribution network in Test Case 1.

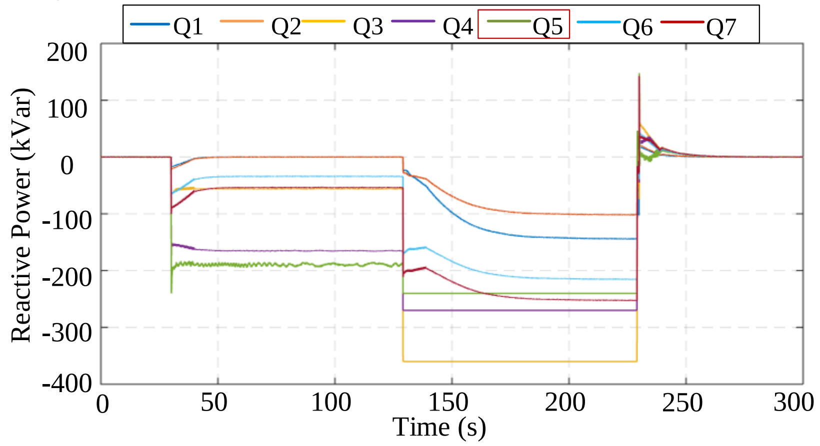

Fig. 5. Reactive power output of each inverter in Test Case 1.

4.2. Test Case 2: Communication Delays

In Test Case 2, the performance of the proposed control method with communication delays is investigated. The test system conditions remain same as in Test Case 1. Two types of communication delays are considered: (i) a constant time delay $\tau_1(t)$=0.5s, and (ii) a variable time delay representable by Gaussian distribution as:

$$\tau_2(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \text{ s}$$

where mean value μ=0.15 and variance σ^2=0.05.

Fig. 6 compares the voltage profiles of the hardware PV inverter (bus 5) with these two communication delays. The PHiL results prove that the proposed method can work properly under bounded communication delays.

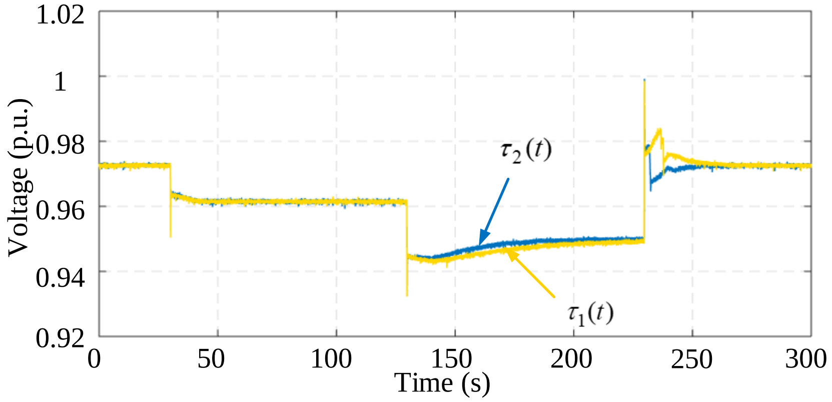

Fig. 6. Voltage profiles of real hardware PV inverter at bus 5 with two types of communication delays.

4.3. Test Case 3: Voltage Rise with Real PV Data

In Test Case 3, the ability of the proposed control approach to mitigate voltage rise conditions arising from high PV penetration is tested. Such a situation usually occurs during the daytime within a distribution grid, when the load demand is minimal while PV generation is at its peak. Therefore, the PV capacity is slightly oversized to a ratio of 1.1 to enable provision of reactive power output even under peak PV generation. The line resistance is increased by ten times (compared to the previous studies, Test Case 1 and 2) to enable emulation of voltage rise issues experienced in weaker, more resistive distribution grids. The communication delay is considered as $\tau(t)$=0.1s. The load percentage is set to 40% while any variations in load are ignored.

The network voltage profiles and the corresponding reactive power outputs have been shown in Fig. 7 and 8, respectively. As can be observed from Fig. 7, the network voltages are always regulated within $[\underline{V}, \bar{V}]$, expect for very short transient periods. The PHiL results reinforce the ability of the proposed control approach to: (i) mitigate voltage rise issues and (ii) work under real world PV data.

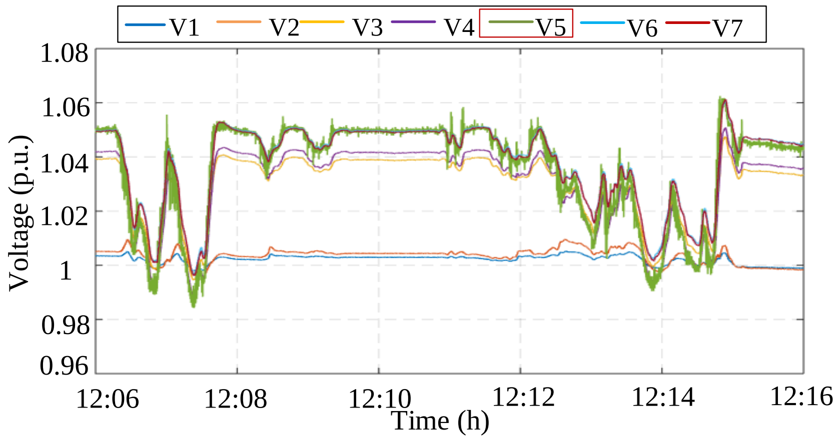

Fig. 7. Voltage profiles in Test Case 3.

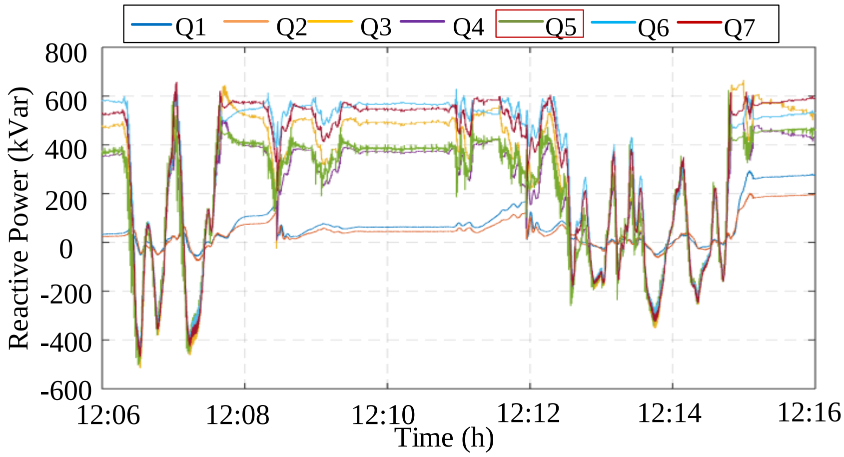

Fig. 8. Reactive power output of each inverter in Test Case 3.

5. Conclusion

- A decentralized and distributed coordinated voltage control which consist of three control hierarchy has been proposed.
- A 7-bus distribution network with inverter hardware has been built based on RTDS platform. The performance of the proposed control approach has been validated using the PHiL experimental platform.
- The experiment results have demonstrated that the proposed method can deal with both the voltage fluctuations and voltage limits violation problems autonomously.
- It has been validated that the proposed control method can operate properly under communication delays.
- Future research regarding to coordinated voltage control by energy storage and communication delay issues will be further investigated.

6. References

[1] P. C. Kotsampopoulos, F. Lehfuss, G. F. Lauss, et al., "The Limitations of Digital Simulation and the Advantages of PHIL Testing in Studying Distributed Generation Provision of Ancillary Services," in IEEE Transactions on Industrial Electronics, vol. 62, no. 9, pp. 5502-5515, Sept. 2015.
[2] E. Guillo-Sansano, A. J. Roscoe and G. M. Burt, "Harmonic-by-harmonic time delay compensation method for PHIL simulation of low impedance power systems," 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), Vienna, 2015, pp. 560-565.