Experimental Analysis of Distribution Network Voltage Regulation Using Smart Inverters

Preprint

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Experimental Analysis of Distribution Network Voltage Regulation Using Smart Inverters

Rasel Mahmud[1], Subhankar Ganguly[1], Jing Wang[1], Killian McKenna[1], and Ning Li[2]

***Abstract*—Smart inverters (SIs) have demonstrated their potential to provide grid services for both transmission and distribution systems. One of these grid services, distribution network voltage regulation by SIs, has the potential to improve network voltage regulation through controlling the reactive and active power output of the SIs. Voltage regulation by SIs will be distributed and might be better suited to controlling local conditions to complement traditional voltage-regulating assets, e.g., tap-changing transformers, capacitor banks, and line voltage regulators. There is a gap in the literature on comparing the SI response characteristics when the SIs are controlled by a local controller or external control signals. This paper presents an experimental study to characterize SI reactive power regulation responses to two different control methods: autonomous control and remote dispatch. We found that SI reactive power regulation responses exhibit important differences between these methods in terms of delays and ramp rate. Finally, power-hardware-in-the-loop (PHIL) tests were conducted to evaluate the performance of these two methods. The PHIL test results show that the SI response characteristics for autonomous control and remote dispatch need to be considered when planning for distribution network voltage regulation using SIs.**

I. Introduction

Utilities have traditionally employed legacy equipment (such as on-load tap-changing transformers, capacitor banks, and line voltage regulators) for distribution network voltage regulation. This voltage-regulating equipment is usually installed at either the substation or along the feeder primary [1] to help reduce voltage drop along the network and ensure that end-of-line voltages remain within service limits. The integration of distributed energy resources (DERs)—in particular, solar photovoltaic (PV) systems with smart inverters (SIs)—brings challenges and opportunities to voltage control. DERs are typically interconnected along the length of the distribution circuit and and can provide grid-edge voltage control by modulating reactive or active power in response to local voltage conditions [2], [3].

In general, voltage regulation by SIs can be realized in two ways: *i)* by remote dispatch method and *ii)* by autonomous SI control. In remote dispatch method, the SI receives external control signals, potentially from a centralized DER management solution, using appropriate communication channels. The external controller could be a centralized [4] or distributed controller [5] that coordinates multiple assets in the network to achieve some control objective, e.g., distribution network voltage regulation, and it might or might not use the SI local voltage measurements in the decision-making process. To leverage the communication-based DER management solution, DERs need to have interoperability with the external controller and access to the communication networks [6]. In distributed control, DERs can act autonomously based on local information (e.g., voltage, frequency, active and reactive power) and predefined functions (e.g., volt-var, frequency-watt) without requiring any communication with any external controller [7].

Voltage regulation using autonomous SI control has been extensively investigated in both simulations and field tests [8]. The configuration, operation, and demonstration of autonomous SI control has been extensively tested and analyzed in the laboratory [9], [10]; however, there is lack of literature on the response and characterization of DERs controlled by remote dispatch method and contrasted with autonomous SI control. Currently, few DERs installed in the field are connected with utility communication networks, and the lack of understanding of centralized control has been a barrier to DER utilization in voltage regulation. Many inverters installed in the field can be connected with the appropriate communication systems using necessary gateways to leverage the benefits of remote dispatch method. It is necessary to continue the discussion on establishing interoperable communications between existing, field-deployed SIs and external controllers to understand the potential of using DERs in centralized voltage regulation schemes.

To address these issues, we developed an experimental setup to investigate and characterize the SI inverter responses for both control modes. The experimental tests were designed to focus on establishing, debugging, and characterizing remote dispatch method and autonomous SI control. The objectives were as follows:

- Demonstrate the successful operation of communication-enabled remote dispatch method for SI control.
- Propose characterization parameters and evaluate the performance of autonomous and remote dispatch control methods of SIs.
- Compare the SI responses in remote dispatch method versus autonomous SI control operation.

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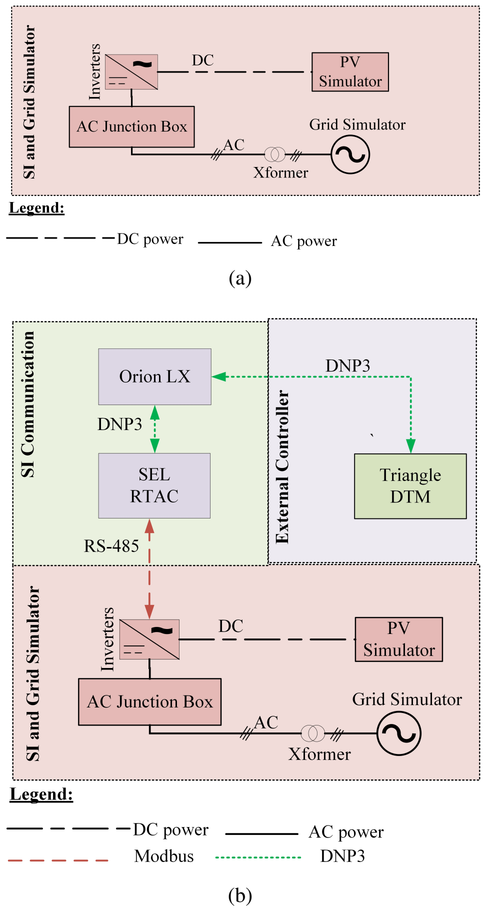


Fig. 1. Experimental setup to evaluate the performance of grid services from smart inverters: a) autonomous SI control, b) remote dispatch method.

- Perform a scenario analysis using remote dispatch method and autonomous SI control.

II. Testing Protocol and Methodology

A. *Overview of Experimental Setup*

An experimental setup was developed using a commercially available, off-the-shelf 125-kW PV inverter to test the autonomous SI control mode of operation, as shown in Fig. 1a. In this setup, the inverter was connected with a 270-kW rated, three-phase grid simulator on the AC side through a 480-V/600-V transformer and a 250-kW rated PV emulator on the DC side. AC-side measurements were taken on the inverter side of the transformer. A setup similar to that shown in Fig. 1b was developed to evaluate the remote dispatch method. For the test setup shown in Fig. 1b, the Triangle Microworks, Inc., Distributed Test Manager (DTM) [11] was used as the remote server to emulate the remote dispatch controller. The communications between the SI and the remote server are described in II-B.

B. *Communications Between SI and Remote Server*

The communications between the SI and the DTM are shown in Fig. 1b to represent a potential field installation scenario. The SEL Real-Time Automation Controller (RTAC) was represented as a data concentrator for the SIs communicating over serial using the RS-485/EIA-485 interface. The data points exchanged over serial were mapped to Distributed Network Protocol 3 (DNP3) [12] points in the RTAC. Also, the RTAC was configured as a DNP3 outstation device to interchange data points with OrionLX using the DNP3 protocol. OrionLX was included in the setup to represent a utility substation data gateway. Finally, the remote server functionality was simulated in the DTM. The DNP3 protocol was also used for the communications between the DTM and OrionLX. A basic heartbeat logic was developed in the RTAC using the IEC 61131 [13] programming language to check the integrity of the communications between the SIs and the DTM. If any communication failure with the remote server was detected, the logic was configured to restore the SI set points to the values stored before the initialization of the communication session. The algorithm for the remote server functionality was developed in the DTM using Javautonomous SI controlript [14]. The remote server was programmed to initiate and terminate the communication session with the SIs and to send active and reactive power set points to the SIs. The set points were calculated based on the measured SI terminal voltages and the volt-var curve programmed in the DTM and automatically dispatched to the SIs.

C. *SI Characterization*

A quantitative comparison of the two SI control methods can be obtained based on the inverter responses to different situations. The Triangle DTM was programmed with volt-var curves to remotely sense the inverter terminal voltages and issue the corresponding reactive power dispatch. This allowed for validating the proposed communication paths and characterizing the response times. Both open-loop and closed-loop tests were conducted, defined as follows:

- Open-loop: The DTM directly issues reactive power set points to the inverter.
- Closed-loop: The DTM receives the inverter terminal voltage, calculates the reactive power based on a pre-defined volt-var curve, and issues the reactive power set points to the inverter.

The volt-var functions described in IEEE 1547-2018 specify categories with parameter values for defining the volt-var curve and the allowable ranges for those parameters; however, it is common in the industry to use non-default volt-var curves [15] to meet the requirements of the grid considering local conditions. Considering all these factors, the test setup was developed to demonstrate the following capabilities:

- Program the inverter for custom volt-var curves.
- Send inverter terminal voltage measurements to a remote server
- Issue active/reactive power dispatch command from a remote server to the inverter

Same volt-var curve was programmed in the inverter when in autonomous SI control mode of operation and in the remote server (DTM) when in remote dispatch method mode of

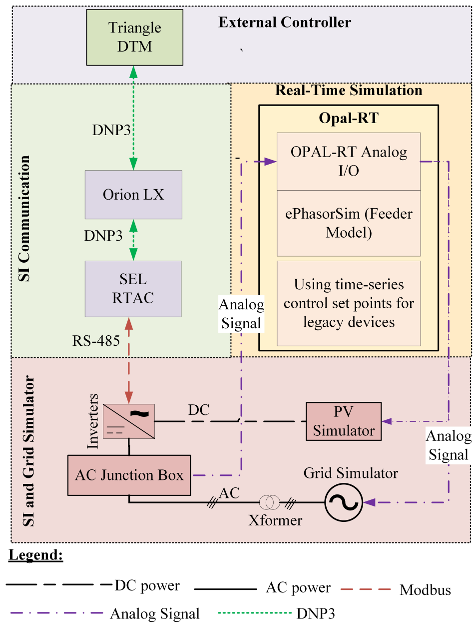


Fig. 2. Experimental setup for scenario analysis using real-time network model.

operation so that the responses can be compared with each other.

D. PHIL set-up for scenario analysis

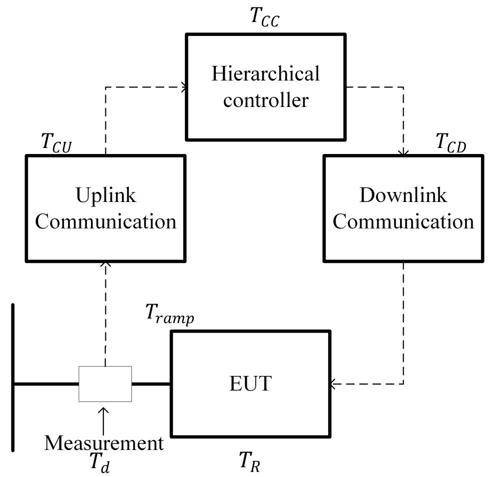
The test setup in Fig. 1b was expanded by including a network model running in real time to regulate the inverter point of common coupling (PCC) voltage, as shown Fig. 2. This power-hardware-in-the-loop (PHIL) setup was used to run different loading and PV generation scenarios. Eventually, the performance of the two different inverter control modes were evaluated in a PHIL testing framework.

E. Real-time Network Model With Legacy Voltage Regulation Equipment

A real-time distribution network model was used in the PHIL test to experimentally evaluate the performance of remote dispatch method and autonomous SI control in distribution network voltage regulation. Separate profiles for all the load and PV generation for the simulated PV units were used in the real-time simulation. Time-series control set points (e.g., on/off status of capacitor banks, line regulator tap positions) for the legacy devices were used to emulate the operation of those devices. The PV simulator was programmed with an irradiance profile for the duration of the tests. The inverter PCC voltage obtained from the real-time network model was used to drive the voltage controlled by the grid simulator. Three scenarios were tested for the inverter control, which are described in Section IV-F.

III. Parameters to Consider When Characterizing SI Response

The parameters to consider when characterizing the SI responses are illustrated in Fig.3b for a generic connection diagram of the equipment under test (EUT), as shown Fig.3a. The local measurements from the EUT were transmitted to an external controller using an uplink communication channel. The external controller processed that information and generated new control set points for the EUT. The control set points were then transmitted to the EUT using a downlink communication channel. The EUT needs some time to receive the control signal, perform the calculation in the local controller, and execute the control set points. The following list summarizes the process and defines the associated parameters:



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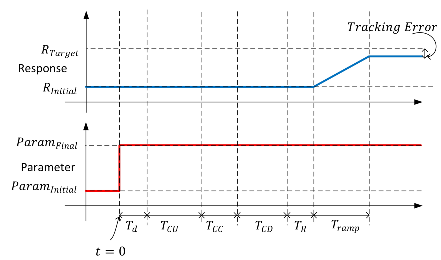


(b)

Fig. 3. Grid services from inverter: a) generic connection and signal flow diagram for the SIs, b) typical response from SIs.

- Detection time (T_d): Time needed to measure the parameter (e.g., PCC voltage)
- Uplink communication latency (T_{CU}): Time needed to transmit the measured parameter from the EUT terminal to the external controller
- External controller computation time (T_{CC}): Time needed for the external controller to compute the control signal for the EUT based on the measured parameter
- Downlink communication latency (T_{CD}): Time needed to transmit the external controller generated control signal to the EUT terminal
- EUT response delay (T_R): Time needed by the EUT to respond to the control signal
- Ramping time (T_{ramp}): Time needed by the EUT to

change the response from one step to another step

- Communication and computational time (T_L): Total time needed to measure the EUT parameter, communicate the parameter to the external controller, compute the external control signal, and transmit the control signal to the EUT
- Tracking error: Difference between the control signal and the actual EUT response.

IV. Experimental Results

The SIs under the autonomous SI control and remote dispatch method modes of operation were characterized by running several experiments using the testing protocols and methodologies described in Section II. Table I provides a summary of these experiments.

A. Remote Dispatch Method (Open-Loop): Reactive Power Ramp Rate

Open-loop tests using remote dispatch method by sending reactive power set points from the DTM to the inverter were carried out to determine the reactive power ramp rate in response to an external control signal. Fig. 4a shows the SI responses when the external control signal requests a change in reactive power from a low value to a high value, and Fig. 4b shows a similar change but in the opposite direction. In this test, the positive reactive power ramp rate was found to be 4.16%/second, whereas the negative reactive power ramp rate was found to be -14.24%/second. The ramping was observed to be linear.

B. Remote Dispatch Method (Closed-Loop): Communication and Computation Delay

Closed-loop tests involving the inverter, the DTM, and the corresponding communication setup were performed to determine the communication and computational loop times (T_L). In these tests, the DTM was programmed with a volt-var function. In this test as shown in Fig. 5, for the step change in the voltage from high to low, the T_L was found to be 11.243 seconds and for the step change in the voltage from low to high, the T_L was found to be 16.1 seconds. Note that the measured T_L reported here were based on two tests. A statistical analysis of T_L from additional measurements is presented in Section IV-E.

C. Remote Dispatch Method: volt-var Dispatched Through DTM

Test case similar to those described in Section IV-B but including step changes in the PCC voltage were used to characterize the closed-loop communication delay; the test results are shown in Fig. 6. We found that the closed-loop communication delay was not constant. One interesting observation here is that there were voltage fluctuations in the PCC voltage near 1.08 per unit (p.u.). The grid simulator voltage was set to stiff in this test case. So, this voltage fluctuation was caused by the transformer impedance and the fluctuation reactive power (closer to maximum reactive power, Q_{max}, output from the inverter) from the inverter.

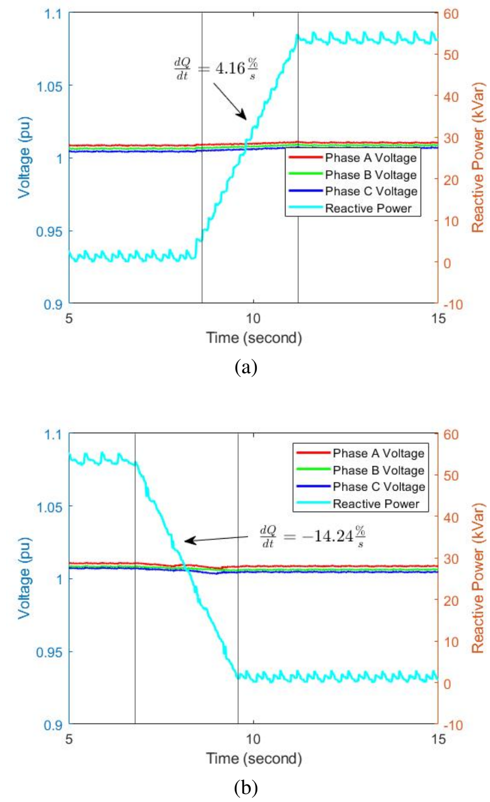


Fig. 4. Test result to characterize the reactive power ramp rate when the inverter was controlled by remote dispatch method: a) positive ramp rate, b) negative ramp rate.

D. Autonomous SI Control: volt-var Programmed at Inverter Local Controller

To compare the performance of the remote dispatch method, the volt-var function with the same parameters from the previous test cases was programmed in the inverter in autonomous SI control. Experimental results are shown in Fig. 7. The mean ramping time (Tramp) was found to be 24.6 seconds with a standard deviation of 2.244 seconds. The reactive power ramping was following a first-order pattern instead of the linear ramp of the reactive power in response to the external control signal.

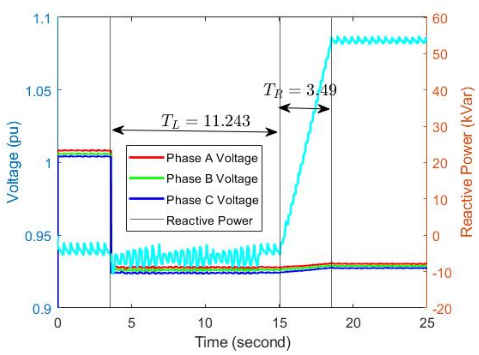
E. Summary of the Characterization Experiments

The observation from all the characterization test results are summarized in Table II. Significant differences are noticeable between the remote dispatch method and autonomous SI control for the same grid voltage conditions. Based on the data shown in Table II, the observed ramp rates and delays for the two control methods need to be considered when planning and designing voltage regulation using SIs. Though fast response from the inverters might be helpful to address disturbances in the grid quickly, there could be potential risks of unintended consequences associated with fast response [7]. Similarly, the inverter response types, e.g. linear, step changes, or PI type responses, might have considerable impact on the overall performance of the voltage regulations when large

TABLE I
CHARACTERIZATION TEST MATRIX

Case #	Description	Test Step	Objective
1	Remote dispatch method: Open-loop DTM to inverter Q command*	Send Q1=0kVar and Q2=55kVar** from DTM to inverter Send Q1=55kVar and Q2=0kVar** from DTM to inverter	1. Determine the ramping time (Tramp).
2	Remote dispatch method: Closed-loop DTM to inverter Q command* (volt-var in DTM)	Change AC PCC voltage from high to low and low to high.	1. Test the interoperability performance between the DTM and the inverters using the applied communication method. 2. Characterize the inverter response in remote dispatch method. 3. Identify any stability and/or unknown issue for inverter control from an external controller.
3	Autonomous SI control: volt-var in inverter	Change AC PCC voltage from high to low and low to high.	1. Characterize the volt-var function in autonomous SI control.

*The Q command refers to reactive power command from the DTM to the inverter.
**Q1 and Q2 refers to different reactive power set points from the DTM to the inverter.



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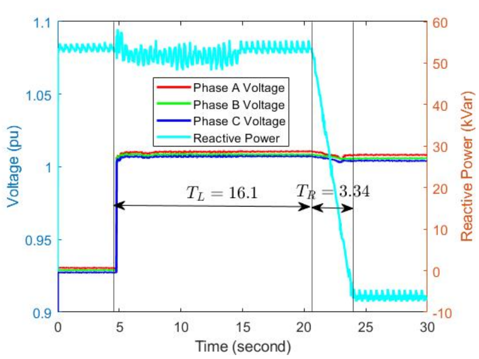

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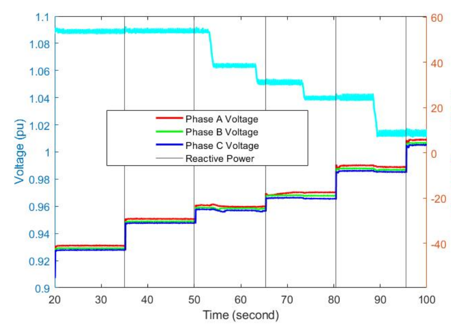
Fig. 5. Test result to characterize the communication and computational delays when the inverter was on centralized control: a) positive ramp rate, b) negative ramp rate.



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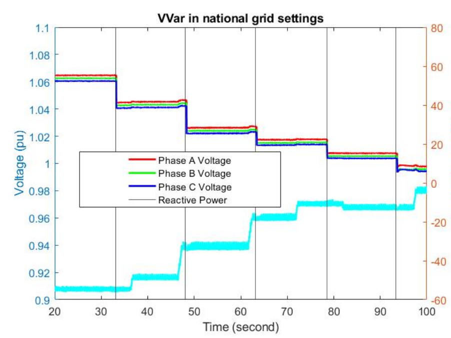


(b)

Fig. 6. Performance of the inverter in remote dispatch method with volt-var hosted in the DTM: a) voltage changes from low to high in steps; b) voltage changes from high to low in steps.

number of inverters are participating in the voltage regulation service either by autonomous control mode or remote dispatch method. Further analysis is needed to evaluate the impact of inverter response types, and ramp rates on grid performance. If it is found that the impact can not ignored for the safe and efficient operation of the grid, inverter manufacturers could consider the inverter controllability options where it is possible to set the way in which inverters respond and the rate/timing/character of response to a change in set-point. Such inverter response controllability options can also be incorporated in the future version of IEEE Std 1547 which currently has limited requirements on inverter response types, and ramp rates.

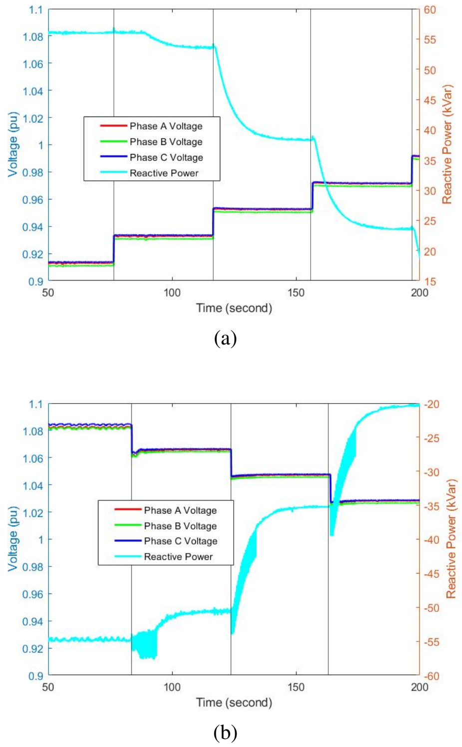


Fig. 7. Test result to characterize the inverter volt-var response in autonomous SI control: a) voltage changes from low to high; b) voltage changes from high to low.

TABLE II
QUANTITATIVE COMPARISON OF REMOTE DISPATCH METHOD TO AUTONOMOUS SI CONTROL RESPONSE

Characterization Parameter	Statistical Parameter	Remote Dispatch	Autonomous Control
T_L [1] Unit: second	Mean	11.74	0.77
	Std. deviation	4.78	0.31
	Maximum	20.16	1.20
	Minimum	2.80	0.20
Positive ramp rate [2] Unit: %/second	Mean	10.87	0.45
	Std. deviation	3.68	0.13
	Maximum	16.26	0.58
	Minimum	6.37	0.15
Negative ramp rate [3] Unit: %/second	Mean	-10.02	-0.49
	Std. deviation	2.96	0.01
	Maximum	-4.50	-0.47
	Minimum	-14.05	-0.51

[1] For autonomous SI control: $T_{CU} = 0$, $T_{CC} = 0$, $T_{CD} = 0$
[2] Rate of change of reactive power from low value to high value
[2] Rate of change of reactive power from high value to low value

F. Scenario Analysis Using the PHIL Test Platform

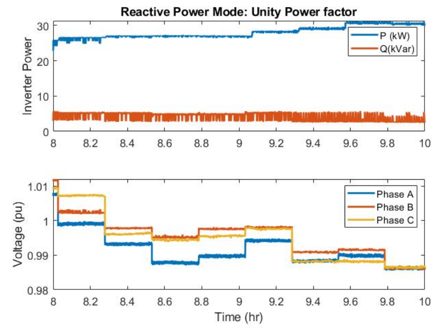
Three different scenarios as explained in Table III were executed using the PHIL setup described in Section II-D. The experimental results from these scenario analyses are illustrated in Fig. 8. These tests demonstrate that voltage regulation can be accomplished by both the autonomous SI control and remote dispatch method modes of operation. The response delay to a changing PCC voltage (e.g., T_L) as well as the reactive power ramping rate impact the network voltage regulation; however, these tests mainly focused on i) the interoperability of the external controller and the inverter and ii) the demonstration of an experimental setup (via the scenario analysis) to examine the performance of autonomous SI control and remote dispatch method for voltage regulation. Detailed performance analysis of any autonomous SI control and remote dispatch method using the setup will need additional experiments.

TABLE III
SCENARIOS TESTING USING PHIL SETUP

Scenario	Reactive Power Mode	Control Model
1	Unity pf	autonomous SI control
2	VVar	autonomous SI control
3	External signal	remote dispatch method

V. CONCLUSION

This paper reports an experimental study demonstrating and validating the communication setup from a remote controller using intermediate communication gateways to an SI. The inverter was able to receive the external control signal for the remote dispatch of the reactive power set points. The study compared the response times of the inverter for remote dispatch method and autonomous SI control. For remote dispatch method, the computational and communication time was found to be within the range from 2–20.16 seconds, and the inverter ramp rates were observed to be within the ranges from 6.3%/second–16.26%/second and from -4.5%/second–14.05%/second. The ramp rates of the inverter in autonomous SI control included the inverter embedded control response and were slower than remote dispatch method. The reactive power ramp rates for autonomous SI control mode averaged 0.45%/second and -0.49%/second. The testing demonstrated the communication paths for a remote dispatch method-controlled inverter to dispatch inverters using remote dispatch controller via the intermediate communication gateways and communication channel. The delays in the communication and response times might be of concern for voltage control, and there might be advantages to using a hybrid communication architecture (i.e., remote control and dispatch but with the ability to receive inverter measurements to update the remote settings from a centralized controller).



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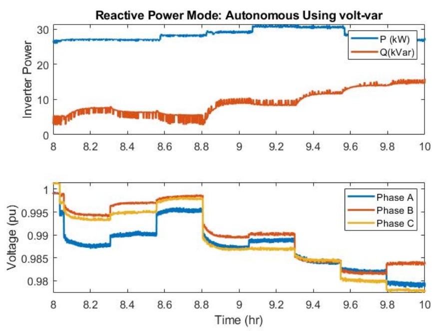

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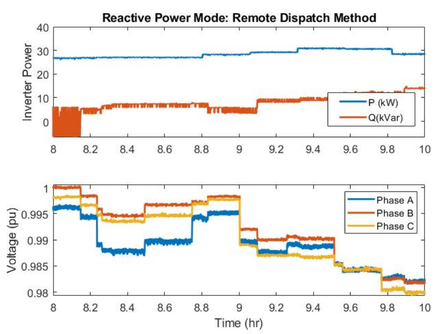

(c)

Fig. 8. PHIL test result to evaluate the applicability of remote dispatch method and autonomous SI control: a) Scenario 1, b) Scenario 2, 3) Scenario 3.

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