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Virtual Power Plant Feedback Control Design for Fast and Reliable Energy Market and Contingency Reserve Dispatch

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Abstract — **An increasing number of state and national interconnection standards are requiring Distributed Energy Resources (DER) to include grid-support functionality. These capabilities along with the growing number of communications-enabled DER make it possible for 3rd party aggregators to provide a range of high-level grid services such as voltage regulation, frequency regulation, and contingency reserves. For the last three years, Sandia National Laboratories has been designing and testing a real-time Virtual Power Plant (VPP) optimization and control platform to provide ancillary services with interoperable DER. In this paper we address the design of feedback controllers for VPPs to meet energy market and tertiary reserve targets. The VPP controller is designed to issue set points to the fleet of DERs to maintain the VPP output within the error margin. This is accomplished by compensating for individual DER losses and output fluctuations with the remainder of the aggregation. The impact of the communication network on the controller design is discussed and simulation results are presented to validate the proposed controller design.**

I. Introduction

The national trend of increasing renewable energy (RE) penetrations is a worst-case scenario for bulk system reliability as grid inertia and governor control are displaced and frequency deviations from RE variability are increasingly common [1]. Therefore, instituting frequency response reserves with DER in accordance with utility, Independent System Operator (ISO)/Regional Transmission Organization (RTO), and NERC requirements are critical for future grid resiliency. Due to the sheer number of DERs and their small sizes, it is not practical for bulk system operators to optimize and control individual DERs. In that regard, a VPP represents a framework for cohesive optimization and control of large numbers of small DERs which are then seen as a single entity by grid operators. VPPs provide grid support services using robust communications, robust control, and efficient optimization of large and diverse sets of DER; and ultimately, this functionality may eliminate the need for dedicated ancillary service thermal plants entirely.

In this work, we choose to focus on the challenge of providing energy market power and tertiary contingency reserves with a VPP. One distinct feature of a VPP serving contingency reserves is that it does not need to have a single point of connection to the grid, but instead composed of an aggregation of different DER sources that connect to the grid at geographically diverse points of common coupling. Therefore, the VPP could be used to aggregate distributed generators, energy storage systems, entire microgrids, demand response units, electric vehicles and even entire distribution stations across an interconnection.

In general, VPPs may be composed of grid operator-owned assets or privately-owned DER that are controlled under a legal agreement. In the case of operating in regions with vertically-integrated utilities, the VPP would be economically dispatched as part of unit commitment planning [2]. In market-based jurisdictions, the VPP would submit offer into the energy or reserve markets [3].

VPP design and optimization has been the subject of number of recent studies. The European Union (EU) has sponsored projects to create a VPP composed of fuel cell DER [4] and the EU FENIX project investigated (a) technical VPPs consisting of DER in one geographical region that accounted for the local power network (e.g., voltage regulation) and (b) commercial VPPs designed to bid into wholesale and other markets [5]. Many researchers have studied VPP bidding mechanisms and market interactions. Centralized bidding strategies for VPPs have been investigated extensively [6]-[8] and a detailed optimization formulation to optimize the day-ahead thermal and electrical scheduling of large scale VPPs has been proposed [9]. Once the VPP is contracted for power delivery, a control system must issue commands to DER to produce the desired aggregate power. A few dispatch architectures have been proposed, including direct, hierarchical and distributed management architectures for VPPs [10] and decentralized multi-agent based techniques for VPP operations [11]-[12]. However, there is little emphasis in the literature on the design and implementation of real-time feedback control for VPP operations.

The main goal of the VPP control system presented herein is to ensure that the real-time total output of the VPP is maintained within an acceptable error margin. This control task is challenging for several reasons. First, the presence of renewable energy DERs in the VPP cause the VPP output to fluctuate. Second, the VPP controller should compensate in real-time for the loss of any particular DER (communication failures, DER disconnection, etc.) or the inability of any DER to attain its reference power output. Third, due to the geographical diversity of DERs in the VPP, a communication network must connect the VPP controller to the DERs through public internet channels. Unlike many previous VPP implementations, DERs included in this work extend down to the residential level (e.g., rooftop microinverters on homes). The presence of the internet-based communication network introduces additional difficulties to the design of the control system due to the effects of communication latencies and data loss. In this work, we present a VPP controller design utilizing PID and proportional controllers to provide fast, reliable aggregate power production.

II. Virtual Power Plant Design

The Sandia VPP is designed with modular components which run as multi-processing servers in a Python environment. The components of the VPP interact to exchange pertinent information through a backend process. The components in the VPP are:

- A forecasting component provides long-term (24-60 hours) forecast of RE anticipated power to the *commitment engine* which provides offers to the ISO/RTO markets, and short term (0-12 hours) forecasts to the *optimization engine*.
- A stochastic *commitment engine* determines the VPP energy and reserve bids based on the maximum expected profit for the required market time period (e.g., day-ahead). A heavy penalty is applied in cases where the VPP cannot meet the power commitments so bids are conservative.
- Once the energy and reserve commitments are established, the stochastic *optimizer* minimizes the operating cost of the VPP over the next 24 hours by determining the setpoints for the DER devices. The optimizer monitors the status of the DERs and—based on short-term DER forecasts and DER availability—the optimizer will charge energy storage systems or start gensets to maintain enough headroom to always meet the commitment.
- To quickly and consistently reach the desired VPP power output, a *centralized controller* is employed to quickly adapt to changes in DER availability, RE power changes, and other DER interoperability or equipment failures.

More detail of the VPP and associated components will be forthcoming in [13].

III. VPP Controller Design

The VPP controller receives optimal dispatch setpoints for each DER from the optimization routine at a specified interval (e.g. every 15 minutes). From this starting operating condition, the VPP controller is responsible for keeping the total output of the VPP within an acceptable error margin from the VPP reference power defined by:

$$VPP_{ref} = E(t) + \alpha(t)R(t) \qquad (1)$$

where E is the energy market commitment, R is the reserve commitment, and α is a binary variable indicating if the reserve is required at time, t.

The design of VPP controllers is challenging for different reasons. First, VPPs aggregate heterogeneous DERs with wide ranges of ramp rates which makes it hard to tune the controller and ensure stable response. Second, the controller has to compensate for small variations in the VPP output due to the variability of RE DER resources and respond to changes in VPP output due to unexpected DER tripping or communication failure. Third, reliance on communication network introduces significant latencies and a probability of data loss which could destabilize the controller.

Fig.1 shows a schematic overview of the proposed VPP controller structure. The optimizer (Optimization Block) resolves for the optimal DER dispatch settings every 15 minutes to account for changes in short-term forecast and other DER status changes — e.g., loss of DER communications. These new setpoints are issued to the VPP controller to re-adjust DER reference powers. The proposed controller consists of the Feedback Controller and the Re-dispatch Processor as detailed below.

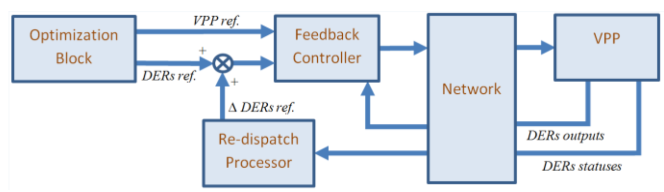

Fig. 1. VPP controller consisting of feedback control and re-dispatch processor.

A. Feedback Controller

The feedback controller is responsible for maintaining the VPP output at the target level by compensating for changes in DERs outputs. The proposed controller structure is shown in Fig. 2 for a VPP with three DERs—though this architecture can be expanded to any number of devices. The controller uses overall VPP error to derive the output of different DERs. Due to the wide range of DER ramp rates, only one DER is equipped with PID controller and the rest of the DERs are equipped with proportional gain control to avoid output ringing.

The DER equipped with PID controller is designated the swing DER of the VPP and is responsible for smoothing the output of the VPP and eliminating any steady state errors. Typically a large storage-based DER should be used as a swing DER to ensure adequate controller response because of its fast ramp ability.

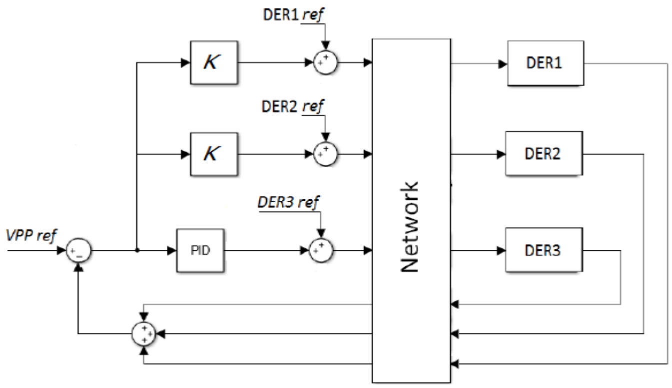

Fig. 2. VPP feedback controller structure.

B. *Re-dispatch Processor*

As shown in Fig. 2, during real-time operation, for large VPP errors, DERs may drift significantly from their reference powers determined by the VPP optimizer. As a result, the VPP operates in a suboptimal economical state. One possible solution to this problem is to actively re-adjust DERs reference powers in real-time to ensure that the VPP output is restored using the most economical DERs. Due to time constraints of real-time operation, it is hard to formulate and solve a complete optimization problem in the re-dispatch processor. However, the initial DER reference powers from the optimizer represents the most economical solution using DER cost curves to meet the VPP bids. Therefore, we propose to dispatch DERs proportional to their initial reference powers. In other words, if P_{error} is the difference between the VPP reference and actual powers—due to communication failures, renewable energy reductions, or tripping of DER k—then for each available DER i in the VPP, the reference output power will be updated as follows.

$$\Delta P_i = P_{error} \frac{P_{i,initial}}{\sum_{m=1,m\neq k}^{N} P_{m,initial}} \quad (2)$$

$$\Delta P_{i,new} = P_{i,initial} + \Delta P_i \quad (3)$$

where, $P_{i,\,initial}$ is the initial output power of DER i before the contingency $P_{m,\,initial}$ denote the output power of DER m.

Note that, once updated reference powers are received from the optimization engine at the beginning of the subsequent optimization period, DERs will follow the new reference powers and the re-dispatch processor will be reset.

IV. Control Simulations

In order to study the impact of different factors on the performance of the VPP controller, a simulated collection of DERs was created based on the equipment located at Mesa del Sol (MdS), Public Service Company of New Mexico (PNM) Prosperity Site, and Sandia's Distributed Energy Technologies Laboratory (DETL) in Albuquerque. The equipment at MdS and Prosperity sites was controlled previously for PV smoothing [14]-[15] so this collection of devices could form a VPP with the correct control structures. The DER included in the simulations is listed in Table 1 with their size, dispatchable power levels, and swing settings.

In order to create a stable VPP controller first the swing controller settings were determined and then the gain was selected for the non-swing DER.

Table I: DER VPP Parameters

DER	Size (kW)	Dispatch-able Power (kW)	Swing?
Miller Cycle Genset at MdS	240	200	No
Diesel Genset at DETL	250	90	No
Battery at Prosperity Site	500	300	Yes
PV at Prosperity Site	500	500	No
Battery at MdS	163	140	No
Fuel cell at MdS	80	40	No
Rooftop PV at MdS	100	100	No
Eight Inverters at DETL	8 x 3	24	No

A. *Controller Tuning*

The swing PID controller for the above VPP was tuned using the Ziegler–Nichols method [16]. The VPP scenario in Table II was simulated, shown in Fig. 3, to illustrate the basic operation of the VPP controller with different controller parameters. For each setpoint command issued to the DERs, a delay and probabatility of packet loss were simulated. The simulation time step was set to 0.01 s but the control setpoints were only recalculated and re-issued every 0.2 seconds to represent the communication delay in sending and receiving power data from the equipment. Fig. 3 shows the performance of the VPP controller which quickly reaches the VPP power reference, but with different overshoot levels and settling times. The final swing control parameters were chosen to be K_p = 0.7, K_i = 1.0, and K_d = 0.

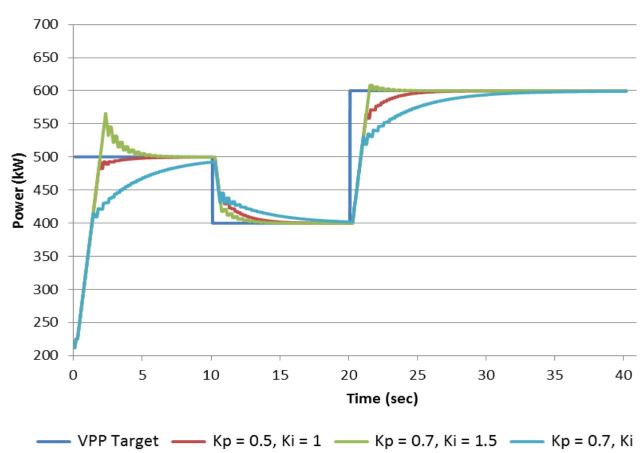

Fig. 3. Swing PID parameters influence on the response of the VPP.

Table II: VPP Operation Scenario

Time (s)	Energy Market Power Commitment (kW)	Reserve Market Power Commitment (kW)	Reserve Request, α
0	500	200	0
10	400	200	0
20	400	200	1

Once the swing controller PID settings were selected, the gain for the non-swing DER was determined. All the PV systems included in Table I were simulated by replaying one of seven 24-hour AC power 1-second datasets recorded and scaled from the 500 kW Prosperity Site PV plant. The effect of K_p gain on the VPP response is shown in Fig. 4. The final non-swing DER gain was selected to be 0.1.

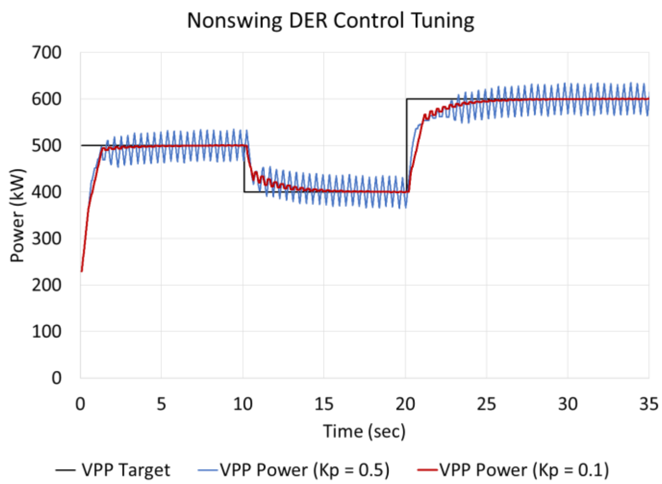

Fig 4: VPP response for two non-swing gains.

B. *Impact of Communication Rate and Delay*

The scenario from Table II was repeated with different communication rates. The control rate is the speed at which new setpoints are issued to the DER and represents the aggregate time to measure the DER outputs and issue new setpoints. Communications to physical DER devices at DETL takes approximately 0.2 sec, which does not significantly influence the stability or effectiveness of the VPP controller, as shown in Fig. 5. It is clear from Fig. 6 that the slower the controller rate is, the more oscillations will appear in the swing DER response as well at the VPP power.

The impact of different communication delays on the VPP response was studied as well. After control information is issued to the DER, the device does not respond for a period of time while the data packet is routed through the communication network. Depending on the transport media, communication protocol, and network topology this time could be quite short (< 10 ms) or relatively long (seconds). In the past, this was a challenge in the MdS and Prosperity PV smoothing project [14] and was ultimately a challenge for the VPP, as described below. Simulations of 100 and 150 ms delays showed the VPP controller was robust to some network latency. The delay in the DER output from network delay is seen when the VPP target changes in Fig. 7.

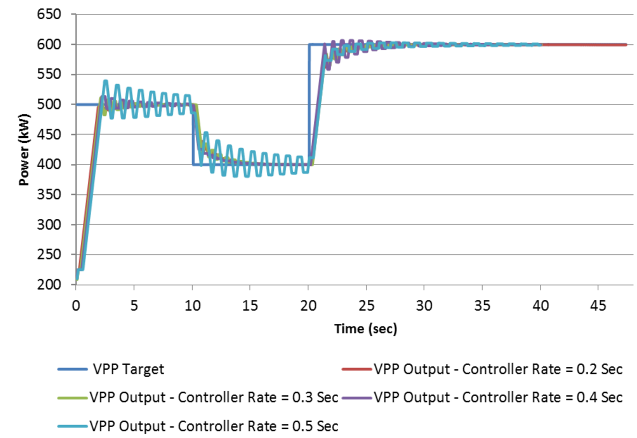

Fig. 5. VPP Output under different controller rates.

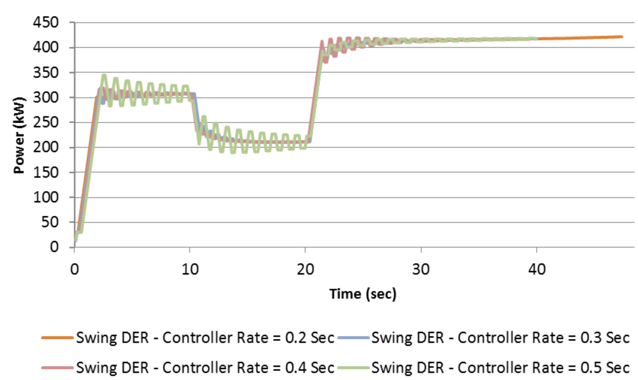

Fig. 6. Swing DER output under different controller rates.

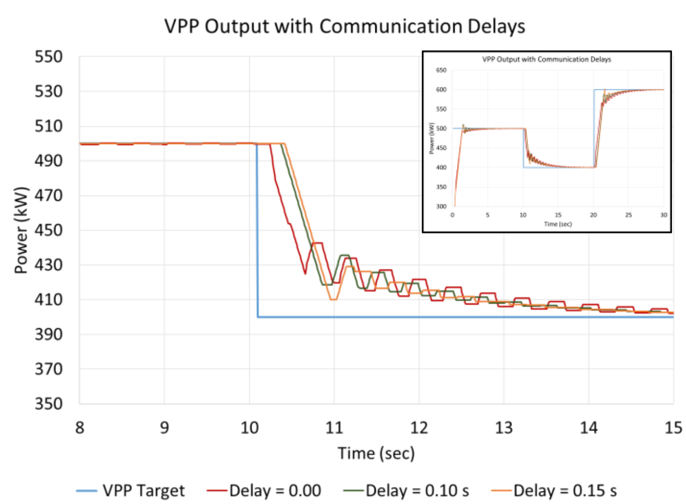

Fig. 7. Influence of DER Delay on VPP output.

IV. Experimental Results

A. *VPP Control with Simulated DERs*

The VPP was run with the tuned control settings, 0.2 second communication rate and no network delay for the scenario shown in Table II. The output of the VPP and the DER devices is shown in Fig. 8.

Next, the commitment and optimization engines were run to determine the energy and reserve bids and DER setpoints for a day in June 2017 based on live forecasts of the DER assets. Data from the controller was captured for 40 seconds with the reserve being called at t = 20 s. The response of the VPP is shown in Fig. 9.

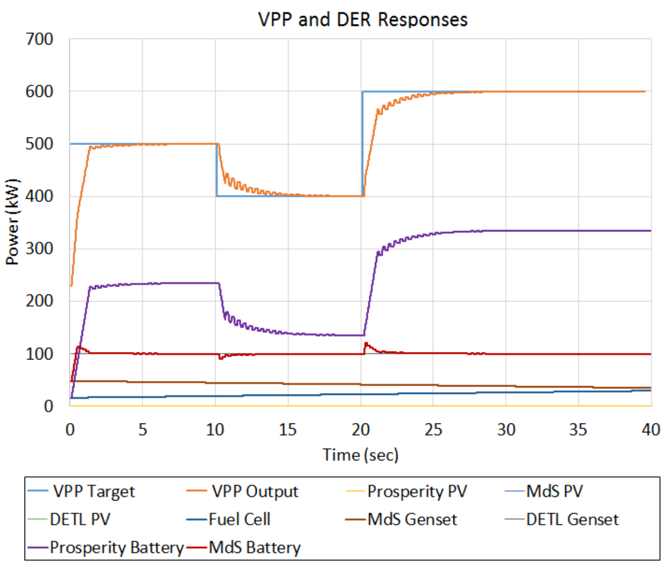

Fig. 8. VPP and DER outputs for a commitment scenario.

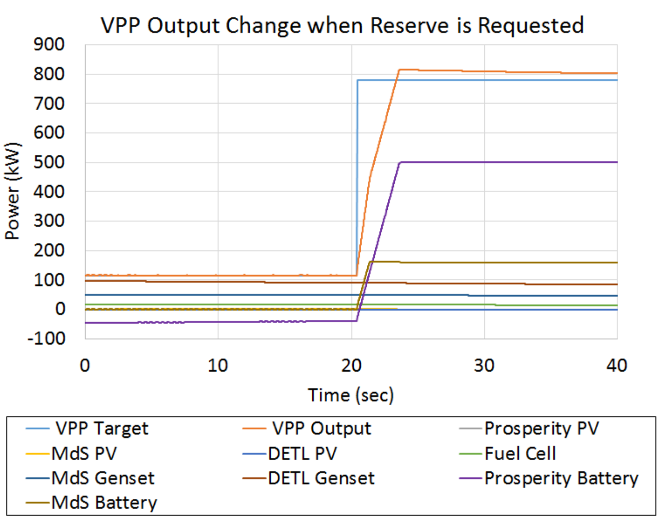

Fig. 9. VPP and DER outputs based on commitment and optimization targets at a time when the reserve is requested.

B. *VPP Control with Real DERs*

To validate the VPP control with a real communication network, three PV inverters in DETL were issued curtailment commands from the VPP dispatch controller via SunSpec Alliance Modbus TCP commands. The DER output power was sequentially read and then the level of active power curtailment of the DER equipment was adjusted. An example of the PV controls reaching a specified power level is shown in Fig. 10. In cases where there was insufficient PV power available, the active power level was not meet, as shown in Fig. 11.

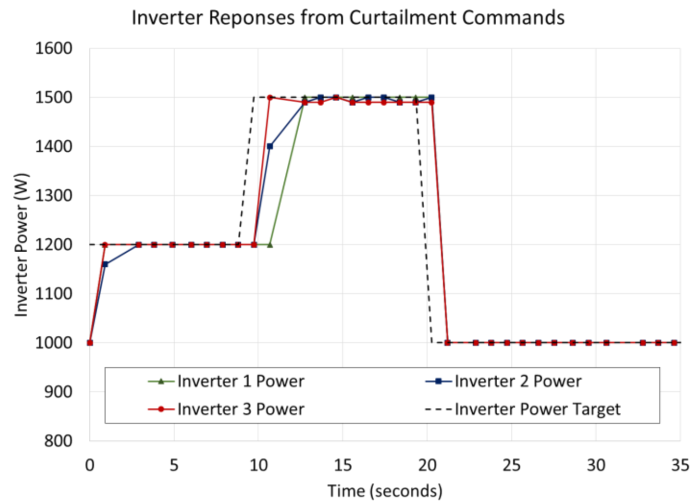

Fig. 10. Response of three inverters to a target power signal.

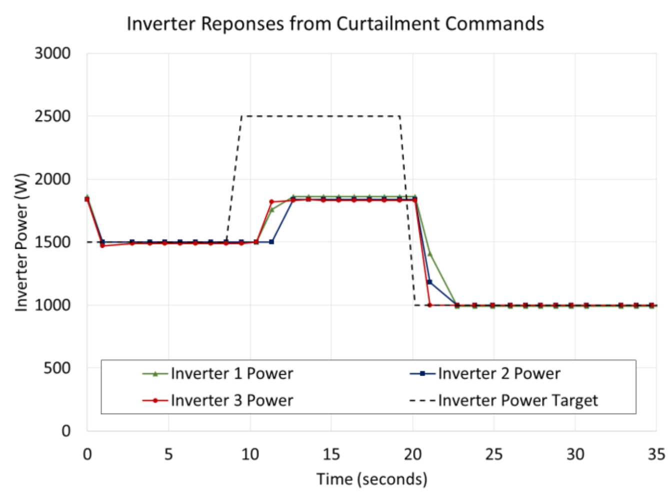

Fig. 11. Response of three inverters to a target power signal, where the power level is above the available power of the renewable source.

Using simulated DER, the control loop was configured to execute in 0.01 seconds, but when adding the physical devices the loop time increased and the duration became variable. As shown in Fig. 12, the read times for the DER was consistently ~200 ms for the inverters, but the write times varied between

~50 and ~1200 ms and the tuned VPP controls were no longer effective. In order to have stable control, the loop time must be consistent, so the variability forced VPP operator to execute the control loop at the largest duration, i.e., 2 seconds. This control speed produced poor VPP system performance. One option to improve the VPP response would be to issue set points via parallelized communications, as opposed to sequentially. This would also allow the VPP to scale as more DER resources are added to the pool.

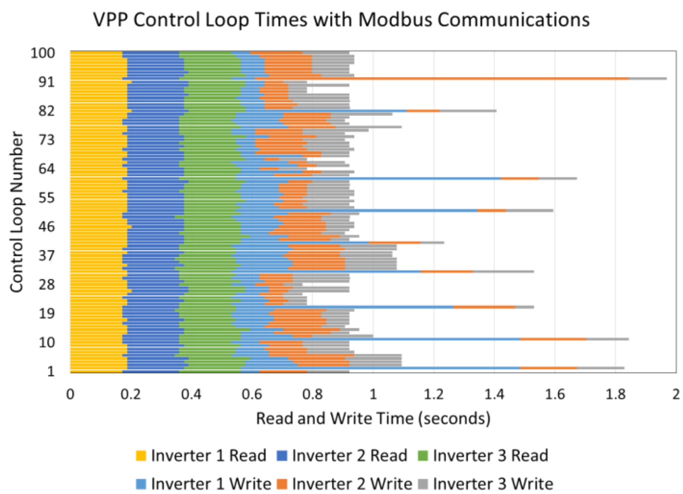

Fig. 12. Inverter read and write rates for three physical DERs.

V. Conclusions

In this paper, a centralized feedback control architecture for virtual power plants was proposed to maintain a reference power output in the presence of individual DER output fluctuations and losses. Simulation results demonstrate the effectiveness of the proposed method for simulated DER devices. The response time and overshoot are appropriate for providing energy and reserve power to ISO/RTO market. In the case of using physical devices to provide this service, significant communication times prevented real time operations. It is recommended to use communication dispatchers, multi-threading or multicast communications to control VPPs to avoid communications-related scaling issues.

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References

[1] C. Martinez, S. Xue, and M. Martinez, “Review of the recent frequency performance of the Eastern, Western and ERCOT Interconnections,” Lawrence Berkeley National Laboratory, Tech. Rep., December 2010.

[2] N.P. Padhy. Unit commitment – a bibliographical survey, IEEE Transaction on Power Systems 19(2):1196–1205, 2004.

[3] M. Shahidehpour, H. Yamin, and Z. Li. Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management, Wiley-IEEE Press, 2002.

[4] A. Dauensteiner, “European virtual fuel cell power plant,” Management Summary Report, Feb 2007.

[5] D. Pudjianto, C. Ramsay, G. Strbac, and M. Durstewitz, “The virtual power plant: Enabling integration of distributed generation and demand,” FENIX Bulletin 2, Feb 2008.

[6] E. Mashhour and S. Moghaddas-Tafreshi, “Bidding strategy of virtual power plant for participating in energy and spinning reserve markets - Part I: Problem formulation,” Power Systems, IEEE Transactions on, vol. 26, no. 2, pp. 949–956, May 2011.

[7] E. Mashhour and S. Moghaddas-Tafreshi, “Bidding strategy of virtual power plant for participating in energy and spinning reserve markets - Part II: Numerical analysis,” Power Systems, IEEE Transactions on, vol. 26, no. 2, pp. 957–964, May 2011.

[8] D. Pudjianto, C. Ramsay, and G. Strbac, “Virtual power plant and system integration of distributed energy resources,” Renewable Power Generation, IET, vol. 1, no. 1, pp. 10–16, March 2007.

[9] M. Giuntoli and D. Poli, “Optimized thermal and electrical scheduling of a large scale virtual power plant in the presence of energy storages,” Smart Grid, IEEE Transactions on, vol. 4, no. 2, pp. 942–955, June 2013.

[10] A. Raab, et al., “Virtual power plant control concepts with electric vehicles,” in Intelligent System Application to Power Systems (ISAP), 2011 16th International Conference on, Sept 2011, pp. 1–6.

[11] M. Vasirani, R. Kota, R. Cavalcante, S. Ossowski, and N. Jennings, “An agent-based approach to virtual power plants of wind power generators and electric vehicles,” Smart Grid, IEEE Transactions on, vol. 4, no. 3, pp. 1314–1322, Sept 2013.

[12] H. Yang, D. Yi, J. Zhao, and Z. Dong, “Distributed optimal dispatch of virtual power plant via limited communication,” Power Systems, IEEE Transactions on, vol. 28, no. 3, pp. 3511–3512, Aug 2013.

[13] J. Johnson, et al. Design and Implementation of a Secure Virtual Power Plant, Sandia Technical Report, 2017 (forthcoming).

[14] J. Johnson, A. Ellis, A. Denda, K. Morino, T. Shinji, T. Ogata, M. Tadokoro, “PV Output Smoothing using a Battery and Natural Gas Engine-Generator,” 39th IEEE Photovoltaic Specialists Conference, Tampa Bay, Florida, 16-21 Jun, 2013.

[15] J. Johnson, K. Morino, A. Denda, J. Hawkins, B. Arellano, T. Ogata, T. Shinji, M. Tadokoro, A. Ellis, “Experimental Comparison of PV-Smoothing Controllers using Distributed Generators,” Sandia Technical Report SAND2014-1546, Feb 2014.

[16] K. Ogata, *Modern Control Engineering*, Prentice Hall, 2010.