Fast Primary Frequency Response Using Coordinated DER and Flexible Loads: Framework and Residential-Scale Demonstration

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Fast Primary Frequency Response using Coordinated DER and Flexible Loads: Framework and Residential-scale Demonstration

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***Abstract*—Methods for supporting grid frequency stabilization using widespread flexible load and DER are becoming essential as the portion of synchronous generation decreases. This article develops a framework for providing fast primary frequency response that leverages deferrable loads and DER coordinated using high-speed measurements in real time to ensure that local objectives are met. The framework is demonstrated in a residential-scale experiment with four household appliances and an inverter. The effectiveness of an example load management algorithm is demonstrated using three underfrequency anomaly test cases. The experimental data corroborates that in all cases, the entire coordinated response, from detection and measurement of a frequency anomaly to completed coordinated net-load response, is completed within 143 ms (~8.5 cycles).**

***Index Terms*—fast frequency response (FFR), frequency response, primary frequency control, flexible load, demand response, distributed energy resources (DER), coordinated response**

I. Introduction

The integration of renewable generation and DER into the electric system continues at a fast pace and is posed to be a permanent trend. These resources are typically coupled to the grid using power electronics rather than rotating generators. The reality of more inverter-coupled generation in addition to related trends is resulting in decreased system inertia and posing challenges toward stabilizing grid voltage and frequency. As such, methods for stabilization of grid voltage and frequency will need to incorporate increased participation from DER. Continuing deployment of information and communication infrastructure is enabling flexible and controllable load to become effective resources for grid frequency regulation when aggregated and coordinated together to create virtual power plants.

There are multiple distinct frequency control levels in power systems. Primary frequency control is typically implemented locally at each generator and works autonomously, usually within 1-3 s after a disturbance, by using droop controllers to adjust speed or output of the generator. Secondary frequency control includes Automatic Generation Control, in which a central controller adjusts the active power output of multiple generators in an area to restore the frequency and power interchanges with other control areas to their target values; this typically occurs within 4 s to 5 min.

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Demand side resources (flexible load) are already being used for both primary and secondary frequency control in power systems. In particular, thermostatically-controlled loads (TCLs)–including heating, ventillation, and air conditioning systems, electric water heaters, and refrigerators–and electric vehicles are often employed because of their inherent energy storage properties [1]. The use of populations of flexible load for primary frequency control generally involves uncoordinated, autonomous controllers that measure local frequency and adjust the demand of the local load, such as those developed in [2], [3]. Such independent uncoordinated action in aggregate has been shown to provide primary frequency response similar to that of a synchronous generator [2]. It has been shown that system frequency disturbances propagate through distribution systems much faster than transmission systems [4]; thus, a collection of devices connected to a distribution system will observe, and can respond to, frequency disturbances just as fast (if not faster) than a traditional frequency response asset (e.g., sync. generator) connected at the same location would.

A number of approaches exist for coordinating and controlling flexible load for secondary frequency control [5]–[10]. Centralized methods for leveraging flexible load within commercial buildings with response at the 2-s [5] and 4-s [6] timescales have been experimentally demonstrated. Decentralized optimal load control strategies with response times on the multiple seconds timescale are developed in [7]–[9]. A hierachichal, communication and control platform that classifies appliances and demonstrates the scheduling and direct load control of appliances on a five min. interval is given in [10].

This article develops a unique solution in which fast (within 10 ac cycles) frequency reserves (i.e., a step response for primary frequency control) are provided by a group of flexible loads and controllable DER that are coordinated together in real time. In contrast to existing primary frequency control approaches, individual resources do not act autonomously based on local frequency measurements and *a priori* control objectives. Here, individual loads communicate with a centralized master controller that reaches an optimal dispatch decision on how to dispatch controllable DER and deferrable load. The framework utilizes high-speed local measurements and ensures that local objectives, which could potentially vary over time, are met. The method offers many of the same coordination and optimal control advantages achieved by approaches for secondary frequency control, but does so on a much faster timescale that is suited for primary frequency control. The framework is developed for use at a building or plant scale where flexibility across multiple building net-load devices can be leveraged, but is also well suited for inclusion in hierarchical or aggregated schemes. The developed approach is experimentally verified using a residential-scale testbed and an example control objective of minimizing the total load deferred while meeting the frequency response target. The platform is flexible in that it is possible to utilize other load/DER combinations and control objectives.

II. Problem Description

A. Problem Description and Terminology

The problem objective is to use a net-load unit, defined as DER and load behind a typical electric customer meter, to provide a rapid (our goal is <10 ac cycles) automated step response to grid frequency disturbances by controlling the unit's DER and load in a coordinated and optimal fashion. Thus, each unit must detect grid frequency; collect measurements from constituent DER and flexible loads; make an optimal decision based on measurements, local objectives (e.g., load priorities and services compensation from the local electric system operator), and global objectives (e.g., change in grid power import/export from each unit towards stabilization of system frequency); and actuate DER and flexible loads, all within 10 ac cycles.

For an example net-load unit, we consider the grid-connected smart residential building shown in Fig. 1. This unit includes a variety of typical household loads, grouped into deferrable and non-deferrable categories (as selected by the user), and an inverter, all connected on a common bus. Let $P_L(t) = \{P_{L,i}(t)\}_{i=1}^{N_L}$ represent the set of power demands from the N_L non-deferrable loads and $P_{Ld}(t) = \{P_{Ld,i}(t)\}_{i=1}^{N_{Ld}}$ represent the set of time-varying power demands from the N_{Ld} deferrable loads. We assume that deferrable loads are turned on or off when issued a command $q^*_{Ld,i}(t) \in \{0,1\}$ such that the effective power is $\hat{P}_{Ld,i}(t) = q^*_{Ld,i}(t)P_{Ld,i}(t)$. The power supplied by the inverter is $P_{G,inv}(t)$ where $P_{G,inv}(t) > 0$ when the inverter is supplying power to the AC bus and $P_{G,inv}(t) < 0$ when the inverter is absorbing power from the AC bus. The inverter must be operated within its ratings $P^{min}_{G,inv} \leq P_{G,inv}(t) \leq P^{max}_{G,inv}$ and could be uni-directional ($P^{min}_{G,inv} = 0$) or bi-directional ($P^{min}_{G,inv} < 0$). The inverter's response to a dispatch command $P^*_{G,inv}$ is very fast; here, we experimentally show an inverter closed-loop response of ~7 cycles. The power imported from the grid is given by $P_{G,grid}(t)$ and has capacity limits $P^{min}_{G,grid} \leq P_{G,grid}(t) \leq P^{max}_{G,grid}$. The power consumed or supplied at each point and deferrable load commands are all assumed to be time-varying quantities; the time dependence (t) is dropped for ease of notation in some cases. By Kirchoff's laws, the (ideal) power consumed from the grid is: $P_{G,grid} = \sum_i^{N_L} P_{L,i} + \sum_i^{N_{Ld}} P_{Ld,i} - P_{G,inv}$.

B. Example Control Objective

The framework developed in this paper is designed to be flexible such that it can be applied to a variety of net-load unit configurations and control objectives. For purposes of demonstration, we choose an example control objective of minimizing the total amount of load that must be deferred while providing frequency response; such an example represents a common scenario. However, a variety of other control objectives and implementations (e.g., prioritizing a set of loads while providing frequency response) can also be supported.

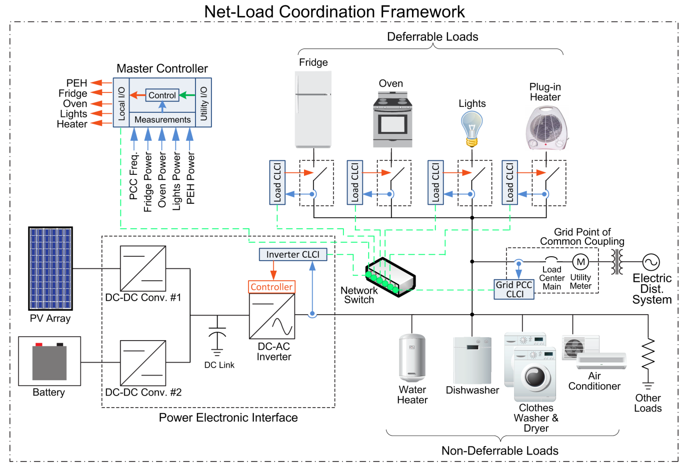

Fig. 1. Residential-scale power system with net load control. Deferrable and Non-deferrable load categories are determined by the user.

We begin by assuming that a net-load unit is incentivized by the local system operator or a local aggregator to provide a net-load response upon detection of a frequency anomaly event, which is defined to be when $f(t) < (f_{nom} - \delta_{f,low})$ or $f(t) > (f_{nom} + \delta_{f,high})$ where f_{nom} is the nominal grid frequency and $\delta_{f,low}$ and $\delta_{f,high}$ are nominal frequency limits (in Hz) below and above f_{nom}. When frequency outside these limits is detected, the net-load unit responds such that:

$$P^*_{G,grid}(t_e + \tau) = (1 - \eta\,\text{sign}(f(t_e) - f_{nom}))P_{G,grid}(t_e) \quad (1)$$

where t_e represents the instant in time in which a frequency anomaly event is detected, τ is the required unit response time, $\eta \in [0.0, 1.0]$ is a parameter defining what percentage of a net-load unit's power output power must be curtailed or increased, $f(t_e)$ is the measured grid AC frequency at $t = t_e$, and $P_{G,grid}$ is the measured power transfer at the grid point of common coupling (PCC) and $P^*_{G,grid}$ is the grid power command. Given an incentive, the net-load unit operator (e.g., a homeowner) then desires to provide this net-load response with minimal inconvenience (e.g., avoid curtailment of loads). Thus, the objective is to provide the desired net-load response by prioritizing the dispatch of the inverter where if the inverter's response cannot satisfy the overall net-load response requirement, the minimum possible deferrable load is curtailed to meet the requirement. This objective can be formalized as:

$$\max_{q^*} \quad \sum_{i=1}^{N_{Ld}} \hat{P}_{Ld,i}(t_e + \tau) \quad (2)$$

$$\text{subject to} \quad P_{G,grid}(t_e + \tau) = P^*_{G,grid}(t_e + \tau) \quad (3)$$

$$P^{min}_{G,inv} \leq P_{G,inv}(t) \leq P^{max}_{G,inv} \quad (4)$$

$$P^{min}_{G,grid} \leq P_{G,grid}(t) \leq P^{max}_{G,grid} \quad (5)$$

Again, the developed framework is flexible so that other objectives, such as load prioritization by the homeowner, could be implemented instead.

The parameter η in equation (1) is chosen to be small and net-load unit operators only commit to η values small enough to guarantee a feasible solution to (2)-(5) exists. A feasible solution to the optimization problem indicates that the new grid power command in equation (1) can be achieved using the capacity available in the net-load unit's flexible load and DER.

III. Methodology and Implementation

The developed framework: 1) implements a centralized master controller for coordinated, optimal dispatch of all net-load resources; 2) realizes and employs a high-speed communication network (e.g., local area network) between each net-load device and the master controller; 3) provides flexible communication interfaces to the control layer at each net-load resource; and 4) implements physical interfaces for high-speed measurement and connection/disconnection of electrical loads. Each of these aspects of the framework are discussed in more detail in the following subsections. The sequence of operations executed in response to each frequency anomaly event is summarized in Section (III-E).

A. Centralized Master Net-load Controller

The central net-load controller leverages high-speed measurements from each net-load resource and an algorithmic implementation of the control objective to provide the optimal and coordinated dispatch of net-load resources for primary frequency response. The principal requirement of the master controller is that it be able to communicate to all net-load resources and solve the algorithm associated with the control objective efficiently. For the demonstration case shown, a Raspberry Pi 3 ARM-based controller met these requirements well, though more powerful local controllers can be leveraged for larger problems.

In the subsequent demonstration, the optimization problem described by (2)-(5) is solved using Algorithm 1. The algorithm determines the optimal inverter set point $P^*_{G,inv}$ and the optimal set of deferrable load on/off set points $\{q^*_{Ld}\}_{i=1}^{N_{Ld}}$ that minimize the total amount of load that must be deferred, while achieving the desired grid import power $P^*_{G,grid}(t_e + \tau)$ as closely as possible. This algorithm is designed for use with residential buildings in which deferrable loads are often appliances that can be shut off quickly (using load control interfaces), but may not be able to be turned on and a known operating point achieved quickly. Thus, in the subsequent demonstration case, both deferrable load and inverter generation are used for response to underfrequency events, but only inverter generation is used for response to overfrequency events. It can be shown (though a proof is beyond the scope of this paper) that this algorithm will achieve the optimal solution to (2)-(5) when: 1) the net-load unit is equipped with a sufficient amount of deferrable load and inverter-based generation; 2) using a η reasonable for the net-load resources available (see discussion in Section II-B); and 3) an underfrequency event occurs. The implemented algorithm leverages dynamic programming to efficiently and dynamically determine the cost associated with each possible load deferrment action from the bottom up. It can be shown that a greedy strategy will not work here; the three test cases in Table I provide counter-examples for a few of the possible greedy choices.

Algorithm 1 Net-Load Management Control Implementation

INPUT: $P_{Ld}[1..N_{Ld}]$, $P_{G,inv}$, $P^{min}_{G,inv}$, $P^{max}_{G,inv}$, $P_{G,grid}$, η, $f(t_e)$, f_{nom}
DO:
Calculate $P_{G,grid\Delta} = \eta\,\mathrm{sign}(f_{nom} - f(t_e))P_{G,grid}$
//Dynamically build the array of all feasible load actions:
Let $P_{Ldo}[1..N_{Ld}]$ be an array of objects with entries $P_{Ldo}[i].power = P_{Ld}[i]$ and $P_{Ldo}[i].idx = i$ for all $i = 1..N_{Ld}$
Let $P_{Ldp}[1..N_{Ldp}]$ be an array of all objects in P_{Ldo} where $P_{Ldo}[i].power > 0$
sort P_{Ldp} in ascending order by $P_{Ldp}[i].power$
Let P_{La} be an empty array //all possible total load set points
$P_{La}[1] = 0$ //corresponds to the case where no loads are curtailed
$P_{La}[2] = P_{Ldp}[1].power$ //case of only the smallest load is curtailed
for $i = 1..(N_{Ldp} - 1)$
  for $j = 1..2^i$
    $P_{La}[2^i + j] = P_{La}[j] + P_{Ldp}[i+1].power$
    if $P_{La}[2^i + j] > P_{G,grid\Delta}$
      //all feasible load actions needed for this $P_{G,grid\Delta}$ have been added
      break out of both for loops
Let $N_{La} = |P_{La}|$ be the length of P_{La}
//first, allocate all available inverter capacity
if $(P^{max}_{G,inv} - P_{G,inv}) \geq P_{G,grid\Delta}$
  $P^*_{G,inv} = P_{G,inv} + P_{G,grid\Delta}$
  $P_{G,grid\Delta} = 0$
else
  $P^*_{G,inv} = P^{max}_{G,inv}$
  $P_{G,grid\Delta} = P_{G,grid\Delta} - P^*_{G,inv}$
//if further reduction required, curtail the minimum total amount
//of load that achieves the required grid power reduction
if $P_{G,grid\Delta} > 0$
  for $i = 1..N_{La}$
    if $(P_{La}[i] \geq P_{G,grid\Delta})$ or $i = N_{La}$
      //build the set of all $q^*_{Ld,i}$ based on the resulting optimal $P_{La}[i]$
      Let $ix[1..N_b]$ be an array with entries corresponding to the N_b-bit binary representation of $(i-1)$ with the LSB in $ix[1]$ //e.g. $4 = [0, 0, 1]$
      for $j = 1..N_b$
        $idx_{orig} = P_{Ldp}[j].idx$ //get the index corresponding to load $P_{Ldp}[j]$ in the original array
        $q^*_{Ld}[idx_{orig}] = (1 - ix[j])$ //curtail cmd. format to on/off format
      $P_{G,grid\Delta} = P_{G,grid\Delta} - P_{La}[i]$
      break
//reduce inverter output by any load curtailment overshoot to
//achieve the minimum deviation from desired grid power
if $P_{G,grid\Delta} < 0$
  $P^*_{G,inv} = P^*_{G,inv} + P_{G,grid\Delta}$
  if $P^*_{G,inv} < P^{min}_{G,inv}$
    $P^*_{G,inv} = P^{min}_{G,inv}$
OUTPUT: $P^*_{G,inv}$, $\{q^*_{Ld,i}\}_{i=1}^{N_{Ld}}$

B. Communication Network

The framework leverages an Internet Protocol communication network for ease of integration and scalability. The subsequent demonstration used a wired ethernet IP network, but the framework also tested successfully with wireless communication. The ZeroMQ distributed messaging platform [11] over the Transmission Control Protocol (TCP) was used to communicate information between devices.

C. Flexible Control Layer Communication Interfaces

Each individual load or DER is interfaced to the control layer through a flexible control layer communication interface (CLCI). In the subsequent demonstration, Raspberry Pi 3 controllers were used as CLCIs. This interface publishes measurements and statuses from each net-load resource onto the ZeroMQ message bus and subscribes to requests and commands from the master controller on the same message bus. In the subsequent demonstration, the inverter's CLCI and local controller are interfaced using serial communication and each deferrable load CLCI is interfaced using analog signals.

D. Physical Deferrable Load Control Interfaces

While many commercial off-the-shelf solutions for controlling loads already exist, none that natively support on/off control of loads and reporting high-speed measurements at the required speed (<10 ac cycles) were found; most existing solutions are designed for slower speeds and in many cases do not include sensors. Thus, custom physical interfaces for high-speed measurement and connection/disconnection of electrical loads are developed. An example of such an interface is pictured in Fig. 2; this interface is designed for single-phase 120V, 15A nominal loads and a second version designed for North American split-phase 240V, 30A nominal loads is also developed. These deferrable load control interfaces are simple to use by connecting in series with the appliance or load's normal house wiring connection using standard NEMA connectors. Each interface includes a solid state relay; fuses for overcurrent protection; high-bandwidth (~200 kHz) voltage and current sensors; analog RMS-to-dc converters; and a CLCI for processing of measurements and interfacing with the control layer.

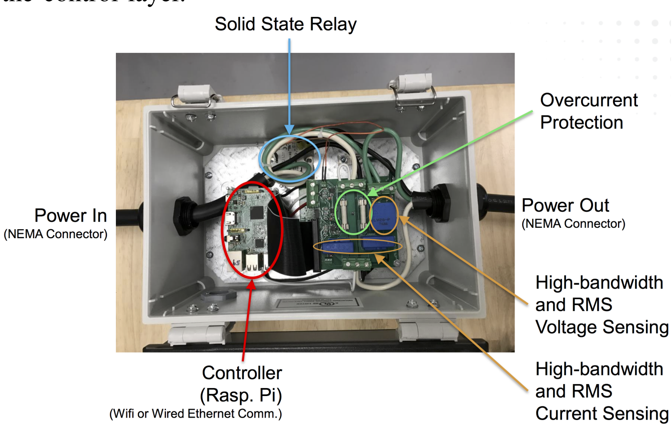

Fig. 2. Physical Deferrable Load Interface

E. Sequence of Operations

1) Grid PCC Measurement Controller: Detects grid frequency anomaly and communicates (via its CLCI) $f(t_e)$ and $P_{G,grid}(t_e)$, to the master controller
2) Master Controller: Commands all deferrable load and DER resources to provide their latest operating power
3) Each Deferrable Load Controller: Sends (via its CLCI) $P_{Ld,i}(t_e)$ to the master controller
4) Each DER Controller: Sends (via its CLCI) latest operating power (e.g., $P_{G,inv}$ for inverter) and operating capacity limits (e.g., $(-P^{max}_{G,inv}, P^{max}_{G,inv})$) to the master controller
5) Master Controller: Uses measurement inputs and solves optimization problem (2)-(5) to determine $P^*_{Ld,i}$ for each deferrable load and P^*_{inv} for the inverter. Sends out dispatch commands
6) Each Deferrable Load Controller and Inverter Controller: Executes dispatch command received from master

IV. Residential-Scale Demonstration

A residential-scale demonstration using a net-load unit consisting of an inverter and four household appliances in the Energy Systems Integration Facility at the National Renewable Energy Laboratory was completed. As the primary aim of the experiment is to demonstrate the performance of the framework and the particular load management algorithm implemented, the four appliances were all considered as deferrable loads and no non-deferrable loads were included. The specific devices used were a 120V combination refrigerator/freezer (General Electric Profile PSQS6YGY); bank of fifteen 120V compact fluorescent and incandescent light bulbs; a 120V plug-in electric heater; a 240V combination Range/Oven (Maytag MER8674); and a 120V, 1 kW ($P^{max}_{G,inv} = 1000$ W) inverter (custom). As can be seen from the current traces in the top plot of Fig. 3, the fridge and bank of light bulbs both exhibit non-linear loading characteristics, while the plug-in heater and oven were both primarily resistive in nature. We purposely included TCLs and other loads to demonstrate that both types can be leveraged by the framework. Given the fact that $P_{G,grid} = \sum_i P_{Ld,i} - P_{G,inv}$ for this example demonstration, no Grid PCC Measurement Controller was needed and instead grid frequency anomaly detection was implemented using a quadrature phase locked-loop (QPLL) [12] on the custom inverter (and thus, step #1 of the sequence of operations was performed by the inverter and steps #1 and #4 were combined as step #1). Reliabily measuring frequency during rapid transients and making a control decision within the desired time limit can be challenging. However, we found that our QPLL implementation, with a choice of gains that traded-off overshoot and settling time, provided reliable, settled, measurements within 1-3 ac cycles throughout all rapid transients we tested. Further background on QPLLs and their superior performance vs. other frequency detection methods during grid transients can be found in [12].

As described in Section II-B, the control objective implemented was to minimize the total amount of load deferred while providing the desired net-load response. The following test cases examine three scenarios involving the same loads and inverter, but varying net-load response target (varying η) and actual load measurements. Each test case began with the appliances turned on for some time and the inverter exporting power at ~80% (800 W) of its nominal power rating. A step in grid frequency from 60 Hz to 59.7 Hz was then initiated. The inverter detected the frequency anomaly ($\delta_{f,low} = 0.25$ Hz was used) as part of step #1 in the sequence of operations listed in Section III-E. For each test case, the measurements listed in the "Start" column of Table I were received from each resource by the master controller. The master controller then determined final load on/off status and inverter set points as

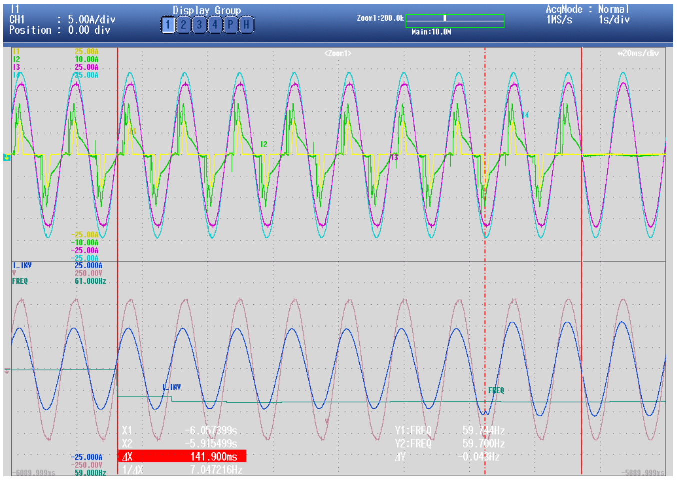

Fig. 3. Oscilloscope screenshot showing time series waveform results for Test Case #3. The top plot shows current meas. for each deferrable load including the fridge ("I1", yellow), bank of light bulbs ("I2", green), plug-in heater ("I3", purple), and oven ("I4", cyan). The bottom plot shows the grid voltage (pink), calculated grid frequency (green), and inverter current (blue). It can be seen that the entire net-load response sequence is completed within 142 ms (~8.5 ac cycles).

shown in the "Finish" column based on the results obtained by executing Algorithm 1.

TABLE I
INPUT CONDITIONS AND FINAL RESULTS FOR TEST CASES

	Measured Power (W) at Start and Finish of Case					
	Test Case #1 ($\eta = 0.09$)		**Test Case #2** ($\eta = 0.14$)		**Test Case #3** ($\eta = 0.17$)	
Resource	**Start**	**Finish**	**Start**	**Finish**	**Start**	**Finish**
Fridge (I1)	146	146	175	175	147	0
Lights (I2)	411	0	409	0	402	0
Plug-in Heater (I3)	1360	1360	1360	1360	1345	1345
Oven (I4)	2827	2827	2850	2850	2793	2793
Inverter	-797	-742	-801	-911	-802	-949
Total	3947	3591	3993	3436	3885	3227
$\Delta P_{G,grid}$		9.02%		13.95%		16.94%
Response Time (ms)		142.6		141.8		141.9

In Test Case #1, 9% (355 W) of the total measured net-load needed to be deferred. This amount was more than the smallest load and the remaining generation capacity of the inverter and so the next largest load (411 W) had to be curtailed. However, once curtailed, constraint (3) determines that the optimal solution should defer as nearly 9% of the net-load as possible. Thus, Algorithm 1 results in inverter's output being reduced. In Test Case #2, 14% (559 W) of the measured net-load was to be curtailed. This required at a minimum that the second largest load (409 W) be curtailed. However, after that load was curtailed the smallest load (175 W) could also have been curtailed, but it was not because the inverter's remaining capacity (200 W) was sufficient to meet the desired set point and the main objective (2) is to minimize the amount of load to be curtailed when possible. Test Case #3 requires a little larger net-load curtailment (17%, 660 W) than Test Case #2 that makes the lights curtailment and inverter output increase no longer sufficient to meet the net-load curtailment requirement. Thus, the optimal solution is to curtail both of the two smallest loads and then meet the remaining net-load reduction requirement using an increased inverter output. In all three test cases, the entire sequence of operations, from detection and measurement of a frequency anomaly to completed actuation of coordinated net-load response, is completed within 143 ms (~8.5 cycles). An oscilloscope screenshot showing waveform results for Test Case #3 is shown in Fig. 3.

V. Conclusions

This paper developed and demonstrated a framework for provision of fast primary frequency response using coordinated deferrable loads and DER. This approach has the unique aspect of providing a fast response appropriate for primary frequency control, but doing so using a group of net-load resources that is coordinated in real-time in order to maximize local objectives. The framework is flexible such that a variety of deferrable load and DER devices can be controlled using configurable CLCIs and a variety of objectives for the optimal net-load management scheme can be defined. The use of this approach in aggregation will enable wide-spread flexible load and DER to provide significant grid ancillary services that help stabilize the emerging low-inertia grid. Future work will further investigate the use of this approach on a larger scale and its coordination with existing synchronous generators providing ancillary services.

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