Cost-Benefit Analysis of Grid-Supportive Loads for Fast Frequency Response

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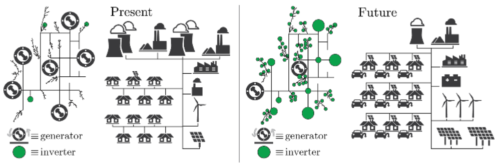
Motivation

- The electric grid relies on synchronous machines to maintain 60 Hz frequency and system inertia[1].

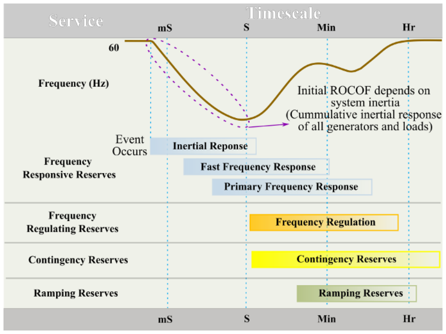


Source: https://www.nrel.gov/grid/grid-forming-inverter-controls.html

- **Inverter-based resources (IBR)[2]**
  - Reduce inertia and increase frequency fluctuation
  - Potentially reduce frequency responsive resources

Types	Synchronous Machines	IBRs
Generators	Fossil Fuel, Hydro, Nuclear	Solar PV, Wind Batteries
Loads	Synchronous Motors Induction Motors	EV Chargers Power Electronic Loads Variable Frequency Drives (VFDs)

- Fast frequency response (FFR) refers to rapid delivery of active power increase or decrease by generation or load within few sec.
  - Quickly rectify a mismatch between supply and demand

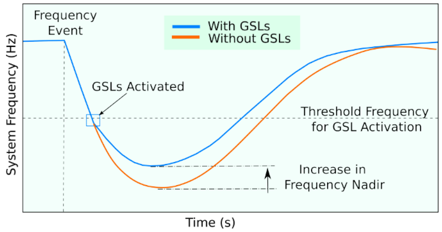


Source: https://www.nrel.gov/docs/fy19osti/72578.pdf

- **IBR generators can provide FFR** to:
  - Lower the inertia requirement
  - Prevent under frequency load shedding (UFLS) events
- **IBR generators have limitations**
  - PV and wind must be curtailed to provide up-regulation FFR
  - Batteries being expensive and limited by its life span for FFR
  - ISOs like ERCOT spends $100m annually on procuring reserves
- **IBR loads can supply FFR with minimal impact on the device or end user** [2]

Grid-Supportive Loads

- Grid-Supportive Load (GSL) is a power electronics-based device that can **autonomously adjust its power consumption based on grid measurements**, for example grid frequency or voltage



- GSLs operate without requiring communication
  - Quickly detect frequency deviations and respond to system imbalances
  - More resilient to cyber attacks compared to traditional demand-side management

Technical Potential and Cost

- Technical potential of GSLs to deliver FFR services for a given end use depends on three parameters [2]:

$$Potential(t) = P(t) \times f_{GSL} \times k$$

- **EV chargers and refrigerators** are promising for FFR services[2]
- Implementation costs for GSLs include **hardware costs for enabling GSL functionality**
  - Voltage divider, isolated signal amplifier, and extra micro-controller unit (MCU) for main power control
- Line voltage sensing circuit (LVSC) to scale line voltage to signal level, while parts other can be implemented in firmware e.g., PLL
  - **Low voltage system**
    - LVSC is included, isolation not require, might **need extra MCU**
    - E.g., refrigerator, Level 2 EV: **average cost: $0.52**
  - **High voltage system**
    - LVSC is included, **need isolation**, MCU is present
    - E.g., Level 3 EV : **average cost: $3.5**

Compensation and Input Data

- No explicit price for FFR as a service but is generally incentivized as with the other AS
  - Used **$1-$8/MWh** as price range
- **Average lifespan** of refrigerators and EV is taken as **10 years**
- Residential-scale refrigerators data is taken from NREL's End-Use Load Profile (EULP) project
- EV dataset is taken from EV WATTS charging station
  - Does not account for the coincidence factor of charging

Cost-benefit Analysis

- Average power consumption across devices varies with the time, so minimum and average consumption
  - Refrigerator: **40 W** to **70 W** with an average of **55 W**
  - Level-2 EV: **122 W** to **350 W** with an average of **179 W**
  - Level-3 EV: **345 W** to **1200 W** with an average of **605 W**

$$Benefit = P_r \frac{\$}{MWh} \times Po(MW) \times Life(yrs) \times T \frac{h}{yrs}$$

- Using a conservative value of **$1/MWh** for FFR, GSLs can provide **≈ $4 – $50** per device across their expected lifetime
- Net benefit to cost ratio, on average, is almost **7x, 29x,** and **14x** the implementation cost, respectively

Cost-benefit analysis of the GSLs with the minimum incentives of $1/MWh and the average life of 10 years

GSLs Cost-benefit ($)	Refrigerator	L2 EV	L3 EV
Average Cost	$0.52	$0.52	$3.5
Benefit with minimum power	$4.26	$10.70	$30.22
Net-benefit with minimum power	$3.74	$10.18	$26.72
Benefit with average power	$4.81	$15.65	$53.00
Net-benefit with average power	$4.29	$15.14	$49.50

- Using a highest value of **$8/MWh** for FFR, GSLs can provide **≈ $34 – $421** per device across their expected lifetime
- Net benefit to cost ratio, on average, is almost **72x, 238x,** and **120x** the implementation cost respectively

Cost-benefit analysis of the GSLs with the maximum incentives of $8/MWh and the average life of 10 years

GSLs Cost-benefit ($)	Refrigerator	L2 EV	L3 EV
Average Cost	$0.52	$0.52	$3.5
Benefit with Minimum Power	$34.08	$85.63	$241.76
Net-benefit with Minimum Power	$33.57	$85.11	$238.26
Benefit with Average Power	$38.45	$125.24	$423.96
Net-benefit with Average Power	$37.93	$124.72	$420.46

- Minimal value that accounts for maintaining the system's stability and dependability can be the value that is always accessible

Conclusions and Future Work

- economic analysis of GSL compares the cost of implementation with the value of FFR as a grid service
  - FFR benefits are significantly larger than then hardware costs
  - Value can be shared by grid operators and consumers (since it depends on who pays for the added cost)
- Better comprehensive cost estimates and more research is required to better predict future load profiles, technology adoption, and FFR requirements for low-inertia grid.

[1] Y. Lin, J. H. Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. Villegas Pico, G. Seo, B. J. Pierre, and A. Ellis, "Research Roadmap on Grid-Forming Inverters," 2020. https://www.nrel.gov/docs/fy21osti/73476.pdf

[2] M. Blonsky, S. Subedi, and B. Mather, "Assessing the technical potential of fast frequency response in grid-supportive loads," in 2022 IEEE Power Energy Society General Meeting (PESGM), 2022.

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