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Changing the World's Energy Future

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ABSTRACT

The growing adoption of residential distributed energy resources (DERs) introduces more uncertain variability in power grid operation. More importantly, the residential DERs operate behind customers' energy meters, and therefore, the utility cannot "directly" monitor them. Prior approaches to enable visibility into behind-the-meter (BTM) DERs either depend on estimations or require intrusive instrumentation on the customer side. To address the critical need for direct real-time monitoring of BTM DERs, in this paper, we propose a novel approach for utility-side direct real-time monitoring of residential BTM DERs. We utilize high-frequency (> 10kHz) conducted electromagnetic interference (EMI) from residential DERs' grid-tied inverters to monitor their power generation. We discuss the working principle of our approach and present supporting results using three of-the-shelf grid-tied inverters.

CCS CONCEPTS

• **Hardware** → **Switching devices power issues**; **Energy metering**; **Power conversion**; *Renewable energy*.

KEYWORDS

Distributed Energy Resources, Residential, Electromagnetic Interference, Solar

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1 INTRODUCTION

1.1 Motivation

Modern power grids have been subject to greater integration of distributed energy resources (DERs) at various levels. While these DERs can have various configurations, residential DERs almost entirely consist of solar power (i.e., PV systems with or without batteries) due to their size and economic viability. Solar energy was accounted for 3% of the total U.S. electricity generation in 2020 and projected to grow to 20% by 2050 [1]. Residential solar (i.e., residential DERs) was responsible for nearly 20% of the net U.S. solar generation in 2020 [2], and therefore, plays a crucial role in the nation's efforts toward energy sustainability.

Meanwhile, the U.S. power grid has been evolving over the years with the growing electrification of buildings and vehicles [3] and an increasing number of grid-connected storage devices altering the load types and profiles [4]. Studies show that modern power grids are being operated ever closer to their thermal and stability limits [5], making them more vulnerable to uncertainties. Towards that, the growing adoption of residential DERs with intermittent generation is having a detrimental impact [6, 7]. More importantly, *the residential DERs operate behind customers' energy meters, and the utility cannot "directly" monitor them.*

The lack of situational awareness of these behind-the-meter (BTM) DERs has introduced new challenges in existing applications such as net-load forecasting, volt-var control and optimization, and protection planning. For instance, due to the lack of a monitoring system, operators could not predict how much BTM generation would disconnect during the 2018 Angeles Forest event [8]. There was an unexpectedly sharp increase in the net load in this event when 130 MW of BTM PV went offline following a disturbance that also tripped an 860 MW utility-scale PV system. There is a general lack of understanding of how the dynamic behavior of the DERs affects the bulk power grid and its protective systems [9, 10]. Hence, more observability of BTM PV systems is required to develop robust power grid control strategies. Moreover, monitoring the variable DERs will improve the electricity market participation, where accurate forecasting is critical for determining the reserve and ramping requirements in the day-ahead and real-time market operations [11].

On the other hand, the residential DERs are installed on utility distribution feeders, which adds to the challenges of managing the

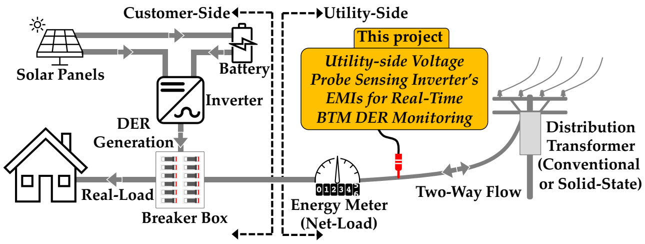


Figure 1: Overview of our proposed approach: We use utility-side voltage probing to capture conducted EMI from grid-tied inverters to monitor the status of DERs.

distribution system. The distributed generation makes the behavior of the distribution system more volatile and worsens existing issues, such as phase imbalance and high-impedance faults [12–14]. The residential DERs can inject power locally, causing reverse power flows and raised voltages [15]. Active monitoring of these DERs helps estimate the current and forecasted distribution system states quickly and accurately, which is vital for many power systems support tools such as market dispatch, transmission energy management, and distribution management system. The state estimation also assists in controlling the power system and protective equipment such as voltage regulators, capacitor banks, breakers, switches, and reclosers.

1.2 Limitations of Existing Approaches

Estimation-based approaches. Prior efforts to enable utility-side visibility into BTM DER, i.e., residential solar generation, have been predominantly based on estimations. For instance, satellite and aerial imagery have been used to identify rooftop PV systems and their characteristics, e.g., size, orientation, and tilt [16–21]. These approaches mainly help estimate the peak solar generation and cannot provide real-time status. Others propose data-driven approaches that extract hidden patterns in the data from feeders and transformers integrated with other information such as solar irradiation and weather condition to disaggregate DER generation [22–24]. Smart energy meter data has also been utilized to gain fine granular customer-level estimations [25–27]. However, separating solar generation and other residential loads from the energy meter's net-load data is challenging as, unlike household appliances with a finite number of active states (e.g., ON, OFF, standby), solar generation changes continuously (depending on the time of the day) and abruptly (due to cloud overcast) [28]. Also, a common downside shared by estimation-based approaches is their reliance on historical data and repeating/predictable load characteristics, making them less effective during irregular grid behavior (e.g., Angeles Forest event [8]) when the accuracy of estimation is critical. Meanwhile, there has been a growing trend of integrating batteries with residential PV systems [29–33]. Batteries inject additional unpredictable variations on the net load due to their charging (i.e., net-load increases) and discharging (i.e., net-load decreases) activities, further diminishing the efficacy of these estimation approaches [34]. To summarize, while useful in some cases, *the quality of the data from existing estimation-based approaches is not sufficient for making real-time operational and control decisions.*

Table 1: The proposed conducted EMI-based approach vs. existing approaches of BTM DER monitoring.

Monitoring Data Source	Direct Measurement	Monitoring PV with Batteries	Homogenous Source	Non-Intrusive Access
Conducted EMI	✓	✓	✓	✓
Solar Irradiation	×	×	✓	✓
Feeder and Transformer	×	×	✓	✓
Smart Meter	×	×	✓	✓
Monitoring Device	✓	✓	×	×
Smart Inverter	✓	✓	×	×

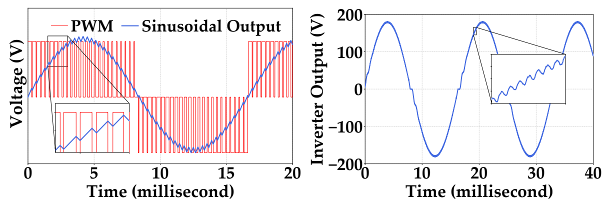
Intrusive sensing. On the other hand, there are commercially available devices for monitoring BTM residential solar generation [35–37]. However, these systems require intrusive instrumentation, for instance, current sensors placed on PV power cables inside the customer's breaker box [35]. An alternative approach is to collect PV generation data directly from smart inverters' monitoring systems [38, 39]. However, the smart inverters report to their respective manufacturers' central data management systems, and the utilities do not have access to these third-party inverter manufacturer data. Moreover, these data sources are challenging to integrate with power utility operations as they come from heterogeneous sources (i.e., different inverter manufacturer's systems) with varying sampling intervals, data integrity, and reliability. Hence, while these monitoring approaches can potentially achieve real-time monitoring, they *require intrusive access and are challenging to integrate with the utility's grid operation.*

1.3 Our Contribution

To overcome the limitations of existing systems, we propose a novel approach for monitoring residential BTM DERs. In our approach, we utilize the conducted electromagnetic interference (EMI) generated by residential DERs' grid-tied inverters to monitor their power generation. We extract the inverter EMI from residential power line voltage for real-time monitoring from the utility side without any intrusive access to the customer equipment. Fig. 1 illustrates our proposed approach where a voltage probe collects high-frequency measurements (10kHz~150kHz) from the utility-side power lines to monitor the BTM DER generation.

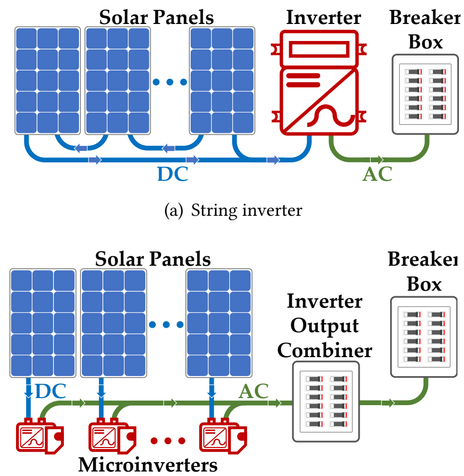
Our approach overcomes the aforementioned limitations in existing BTM DER monitoring systems - (❶) we offer real-time monitoring of BTM DER generation, (❷) we do not rely on any historical patterns/characteristics and directly monitor the DER inverter's power generation, (❸) we can accurately estimate a customer's "real load" by factoring in the DER generation to the energy meter's net-load, and (❹) we enable utility-side and fully utility-managed BTM DER monitoring system. Table 1 compares our proposed approach with existing techniques.

In what follows, we first provide background on grid-tied inverter operation and residential DER architecture. We then discuss the operating principle of our approach, followed by preliminary results. We then discuss the technical challenges and future work.



(a) PWM illustration (b) Actual inverter output

Figure 2: (a) Illustration of PWM-based sinusoidal synthesis in inverters. (b) The output voltage from the SMA inverter shows the voltage ripples due to PWM.



(a) String inverter

(b) Microinverter

Figure 3: Residential DER (PV/solar) architectures.

2 BACKGROUND

Grid-Tied inverters. THD-compliant grid-tied inverters are required to supply sinusoidal outputs at a stable voltage. These inverters use the pulse width modulation (PWM) method for generating the sinusoidal output [40, 41]. PWM inverters use solid-state electronic switches for rapid switching to generate rectangular PWM pulses. As shown in the illustration in Fig. 2(a), by controlling the duty cycle of the PWM pulses, these inverters synthesize sinusoidal outputs using LC filters that extracts the moving average of the input PWM pattern. The rapid switching also creates high-frequency ripples in the inverter output voltage (Fig. 2(a)). Moreover, the high-frequency ripples change with the loading level of the inverter – a higher load creates taller ripples and vice versa. The frequency of these ripples depends on the inverter's PWM switching rate and appears as high-frequency EMIs in the frequency domain [42–44]. Note that the voltage ripples from the inverter are in the millivolts range and therefore contribute very little (if at all) towards the harmonic distortion (and hence do not affect THD compliance), yet still contain information about the inverter operation, and thereby enable our behind-the-meter monitoring scheme.

DER architecture. There are two main types of inverter architectures used in residential solar - string inverters and microinverters [45, 46]. In string inverters (Fig. 3(a)), all solar panels are connected to a single inverter with enough capacity (e.g., 3 $\sim$ 10kW) to handle the aggregated peak generation from the solar panels. The inverter supplies power to the residential load or the power grid through the residential breaker box. In some inverters, the solar panels are also equipped with DC optimizer that help to provide a stable voltage to the inverter [45]. In a microinverter setup (Fig. 3(b)), each solar panel is equipped with a smaller (e.g., 300 $\sim$ 500W) dedicated inverter. The microinverters work in parallel. The inverter outputs are typically combined in a separate breaker box and then connected to the main breaker box.

DERs with batteries. In addition to the PV panel-inverter connectivity architecture, another important aspect of BTM solar system architecture to consider is the presence of energy storage/batteries. There are two main ways BTM solar systems are integrated with batteries - AC-coupled and DC-coupled systems. In AC-coupled systems, the battery is integrated into the AC side of the residential power network. Since batteries are DC sources, AC-coupled batteries require a dedicated inverter-charger for the battery bank. The advantage of an AC-coupled system is that it can independently operate with or without a solar system in place. In DC-coupled systems, on the other hand, the battery is connected to the DC side of the solar system, hence behind the inverter, in parallel with the PV panels. For typical solar inverters, the DC-coupled battery bank is charged only with solar power from the PV panel. Here, DC power from the solar panels is stored in the batteries, and it does not require charging capability (i.e., rectifier) on the inverter. However, a hybrid charger-inverter can charge a DC-coupled battery using power from the grid instead of the PV panel.

3 RESIDNETIAL DER MONITORING

Working principle. Our proposed BTM DER monitoring system is based on the following observations. *First*, we identify that the rapid electronic switching in the inverters of DERs generates conducted EMIs at a high-frequency range (e.g., >10kHz). *Second*, the EMIs from these grid-tied inverters are conducted through the residential power network and can be extracted from utility-side line voltage measurements (e.g., at the energy meter) [47, 48]. *Third*, the conducted EMI changes with changes in inverter loading (e.g., solar generation). Therefore, by *analyzing the line voltage probed at a high frequency, we can extract the operating status of a BTM DER.*

Advantages of our approach. As the conducted EMI changes instantaneously with a change in inverter load, our approach offers real-time status monitoring of the DER generation. Also, in contrast to estimation-based approaches, ours can be considered "direct" monitoring as we do not need to rely on additional information to determine the DER generation. Moreover, as we use power line voltage measurements on the utility side, we do not need intrusive access to customers' equipment or private data.

How to extract inverter EMIs from line voltage? The voltage probe measuring the line voltage captures the inverter's conducted EMIs as well as EMIs from various household appliances and electronic loads [49, 50]. Hence, it begs the question - *how do we extract/separate the inverter's EMI?*

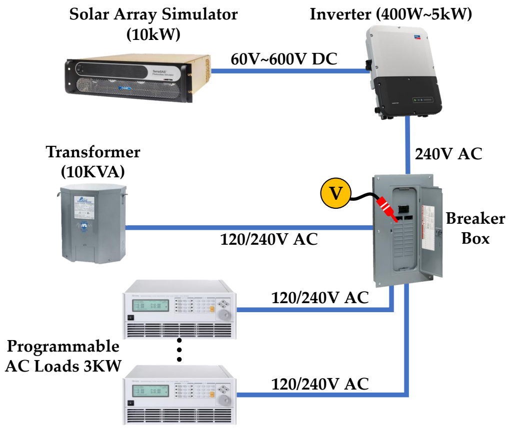


Figure 4: Illustration of our experimental setup.

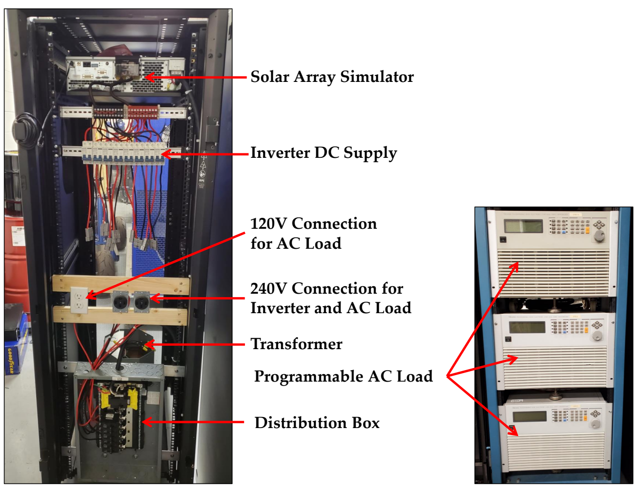
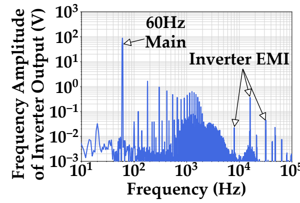
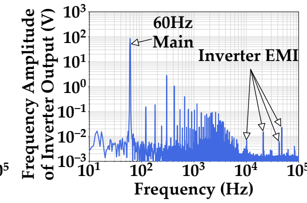


Figure 5: Photo of our residential power testbed.

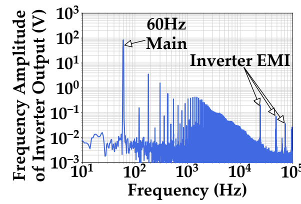
We identified that the characteristics of the EMIs generated by the inverters allow us to isolate them from other EMIs using frequency domain analysis. More specifically, as shown in Fig. 6, the inverter EMIs create clearly identifiable spikes in the frequency analysis of the line voltage. These frequency spikes are generated because the electronic switching in inverters is done at a fixed frequency to simplify the design/choice of an inverter's frequency-sensitive components such as inductors and capacitors [51, 52]. In the frequency analysis, inverter EMI occupies a small frequency band because of the fixed frequency switching. Also, typical inverters' switching frequencies are set in the range of a few tens of kilo-hertz as a higher switching frequency creates better sinusoidal output voltage and, at the same time, allows the use of smaller and cheaper electrical components (e.g., transformers). *The inverter EMIs' narrow bandwidth helps them to avoid interference from other sources, while their high frequency places them away from power grid harmonics - making the inverter EMIs extractable from the line voltage measurement.*



(a) SMA Sunny Boy

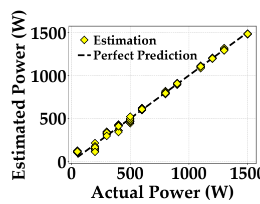


(b) Enphase IQ7

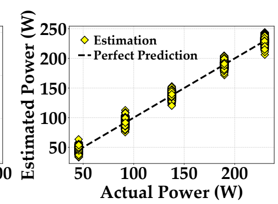


(c) Schneider Xantrax

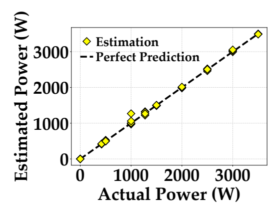
Figure 6: Frequency domain analysis of the output voltage of three different inverters showing their high-frequency EMIs.



(a) SMA (3KW), RMSE = 31W



(b) Enphase (400W), RMSE = 5W



(c) Schneider (3.5KW), RMSE = 43W

Figure 7: Estimating inverter power from EMI using neural network regression on frequency data.

4 PRELIMINARY RESULTS

Experimental setup. In our preliminary study, we run experiments with three different grid-tied inverters - an SMA Sunny Boy 3kW string inverter, an Enphase IQ7 400W microinverter, and a Schneider Electric Xantex XW 4kW hybrid inverter. Our experiment setup consists of a 10KW Ametek Solar Array Simulator, a 10KVA split-phase distribution transformer, a power distribution box, and several AC programmable loads. The solar array simulator powers the inverter under test. The inverter connects to the 240V terminals of the distribution box. We take voltage measurements at the distribution box using an oscilloscope at a sampling rate of 200K samples per second. Fig, 4 illustrates our experiment setup, while Fig. 5 shows a photo of our testbed (without any inverter connected).

Results. Fig. 6 shows the frequency domain analysis (FFT) of the three inverters' output voltage. In each case, we see inverter-generated EMIs in the voltage measurement. These EMIs are created due to the rapid electronic switching of the inverters. We identify these inverter-created frequency spikes by comparing the voltage without any inverter connected.

Next, in Fig. 7, we show the estimation accuracy of inverter power from EMI using Matlab Regression Learner [53]. In this regression, we use the frequency data (Fig. 6) as the input after applying principal component analysis (PCA) to keep only the relevant frequency components. The PCA keeps only one component for SMA, 240 components for Enphase, and two frequency components for Xantrax. Note that the frequency analysis in Fig. 6 has 100,000 frequency components, highlighting that our approach only needs a tiny fraction of the frequency data and, therefore, is unlikely to have significant interference from other EMI sources.

The regression shows that *we can determine the inverter power from the inverter EMI with high accuracy*. We see that across all the inverter models, the root mean squared error (RMSE) is less than 1.5% of their respective capacity, demonstrating the great potential of conducted EMI-based monitoring.

Note that our experiment results also reveal that EMIs vary with inverter models and require different regression models to extract their power information from their EMIs.

5 CONCLUDING REMARKS

In this paper, we proposed a new approach for monitoring residential BTM DERs from the utility side. We discussed the working principle of our approach and presented preliminary results supporting our novel idea.

Technical challenges. Although our preliminary results reveal the untapped potential of utilizing conducted EMI for BTM DER monitoring, the novelty of our approach invites various research challenges toward developing a practical end-to-end solution. (1) The behavior of conducted EMI from DERs has not been studied before in the context of real-time monitoring applications. (2) We need to develop new data processing pipelines and algorithms for extracting and interpreting DER status from conducted EMIs. (3) Our monitoring approach enables new insight into the distribution system that needs careful consideration for integrating with the grid operation. (4) For widespread deployment of our approach, we need to develop a low-cost and retrofittable EMI sensor. (5) We also need to develop new low-power and low-cost communication protocols. (6) We need to ensure the security of the sensor device and the communication channel.

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REFERENCES

[1] U.S. Energy Information Administration (EIA), "Solar generation was 3% of U.S. electricity in 2020, but we project it will be 20% by 2050," 2021. Available at https://www.eia.gov/todayinenergy/detail.php?id=50357.
[2] U.S. Energy Information Administration (EIA), "Solar Electricity Net Generation," 2021. Available at https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.06#/?f=A&start=2000&end=2020&charted=0-10-1.
[3] U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2020," 2020. Available at https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf.
[4] H. Rudnick and L. Barroso, "Flexibility needed: Challenges for future energy storage systems [guest editorial]," *IEEE power and energy magazine*, vol. 15, no. 5, pp. 12–19, 2017.
[5] North American Electric Reliability Corporation (NERC), "2018 Summer Reliability Assessment," 2018. Available at https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_05252018_Final.pdf.
[6] R. Quint, L. Dangelmaier, I. Green, D. Edelson, V. Ganugula, R. Kaneshiro, J. Pigeon, B. Quaintance, J. Riesz, and N. Stringer, "Transformation of the grid: The impact of distributed energy resources on bulk power systems," *IEEE Power and Energy Magazine*, vol. 17, no. 6, pp. 35–45, 2019.
[7] M. Khatibi and S. Ahmed, "Impact of distributed energy resources on frequency regulation of the bulk power system," in *2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE)*, pp. 258–263, IEEE, 2019.
[8] North American Electric Reliability Corporation (NERC), "April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report," 2018. Available at https://www.nerc.com/pa/rrm/ea/April_May_2018_Fault_Induced_Solar_PV_Resource_Int/April_May_2018_Solar_PV_Disturbance_Report.pdf.
[9] North American Electric Reliability Corporation (NERC), "Recommended Disturbance Monitoring for Inverter-Based Resources," 2020. Available at https://www.nerc.com/comm/PC/SMSResourcesDocuments/White_Paper_IBR_Disturbance_Monitoring.pdf.
[10] K. W. Jones, P. Pourbeik, G. Kobet, A. Berner, N. Fischer, F. Huang, J. Holbach, M. Jensen, J. O'Connor, M. Patel, *et al.*, "Impact of inverter based generation on bulk power system dynamics and short-circuit performance," *Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, Tech. Rep. PESTR68*, 2018.
[11] E. Ela, M. Milligan, and B. Kirby, "Operating reserves and variable generation," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2011.
[12] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, "Protection challenges under bulk penetration of renewable energy resources in power systems: A review," *CSEE journal of power and energy systems*, vol. 3, no. 4, pp. 365–379, 2017.
[13] A. Ghaderi, H. A. Mohammadpour, H. L. Ginn, and Y.-J. Shin, "High-impedance fault detection in the distribution network using the time-frequency-based algorithm," *IEEE Transactions on Power Delivery*, vol. 30, no. 3, pp. 1260–1268, 2014.
[14] B. Wang, J. Geng, and X. Dong, "High-impedance fault detection based on nonlinear voltage–current characteristic profile identification," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3783–3791, 2016.
[15] M. Baran, H. Hooshyar, Z. Shen, J. Gajda, and K. Huq, "Impact of high penetration residential pv systems on distribution systems," in *2011 IEEE Power and Energy Society General Meeting*, pp. 1–5, IEEE, 2011.
[16] J. de Hoog, S. Maetschke, P. Ilfrich, and R. R. Kolluri, "Using satellite and aerial imagery for identification of solar pv: State of the art and research opportunities," in *Proceedings of the Eleventh ACM International Conference on Future Energy Systems*, pp. 308–313, 2020.
[17] Google, "Project Sunroof," Accessed, February 2022. Available at https://sunroof.withgoogle.com/.
[18] X. Hou, B. Wang, W. Hu, L. Yin, and H. Wu, "Solarnet: a deep learning framework to map solar power plants in china from satellite imagery," *arXiv preprint arXiv:1912.03685*, 2019.
[19] J. Yu, Z. Wang, A. Majumdar, and R. Rajagopal, "Deepsolar: A machine learning framework to efficiently construct a solar deployment database in the united states," *Joule*, vol. 2, no. 12, pp. 2605–2617, 2018.
[20] J. Camilo, R. Wang, L. M. Collins, K. Bradbury, and J. M. Malof, "Application of a semantic segmentation convolutional neural network for accurate automatic detection and mapping of solar photovoltaic arrays in aerial imagery," *arXiv preprint arXiv:1801.04018*, 2018.
[21] J. M. Malof, L. M. Collins, and K. Bradbury, "A deep convolutional neural network, with pre-training, for solar photovoltaic array detection in aerial imagery," in *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 874–877, IEEE, 2017.
[22] F. Bu, K. Dehghanpour, Y. Yuan, Z. Wang, and Y. Zhang, "A data-driven game-theoretic approach for behind-the-meter pv generation disaggregation," *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 3133–3144, 2020.
[23] E. C. Kara, C. M. Roberts, M. Tabone, L. Alvarez, D. S. Callaway, and E. M. Stewart, "Disaggregating solar generation from feeder-level measurements," *Sustainable Energy, Grids and Networks*, vol. 13, pp. 112–121, 2018.
[24] F. Sossan, L. Nespoli, V. Medici, and M. Paolone, "Unsupervised disaggregation of photovoltaic production from composite power flow measurements of heterogeneous prosumers," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 9,

pp. 3904–3913, 2018.
[25] M. Tabone, S. Kiliccote, and E. C. Kara, "Disaggregating solar generation behind individual meters in real time," in *Proceedings of the 5th Conference on Systems for Built Environments*, pp. 43–52, 2018.
[26] C. M. Cheung, W. Zhong, C. Xiong, A. Srivastava, R. Kannan, and V. K. Prasanna, "Behind-the-meter solar generation disaggregation using consumer mixture models," in *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, pp. 1–6, IEEE, 2018.
[27] F. Bu, K. Dehghanpour, Y. Yuan, Z. Wang, and Y. Guo, "Disaggregating customer-level behind-the-meter pv generation using smart meter data and solar exemplars," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5417–5427, 2021.
[28] X. Chen, M. M. Haji, and O. Ardakanian, "A data-efficient approach to behind-the-meter solar generation disaggregation," *arXiv preprint arXiv:2105.08122*, 2021.
[29] E. O'Shaughnessy, D. Cutler, K. Ardani, and R. Margolis, "Solar plus: Optimization of distributed solar pv through battery storage and dispatchable load in residential buildings," *Applied Energy*, vol. 213, pp. 11–21, 2018.
[30] J. Hoppmann, J. Volland, T. S. Schmidt, and V. H. Hoffmann, "The economic viability of battery storage for residential solar photovoltaic systems–a review and a simulation model," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 1101–1118, 2014.
[31] U.S. Energy Information Administration (EIA), "Most planned U.S. battery storage additions in next three years to be paired with solar," 2021. Available at https://www.eia.gov/todayinenergy/detail.php?id=49756#.
[32] U.S. Energy Information Administration (EIA), "Battery Storage in the United States: An Update on Market Trends," 2021. Available at https://www.eia.gov/analysis/studies/electricity/batterystorage/.
[33] Globe Newswire, "U.s. solar battery market is expected to reach $37.7 million by 2030: Says amr," Accessed, February 2022. Available at https://www.globenewswire.com/news-release/2021/09/15/2297734/0/en/U-S-Solar-Battery-Market-Is-Expected-to-Reach-37-7-Million-by-2030-Says-AMR.html.
[34] C. M. Cheung, S. R. Kuppannagari, R. Kannan, and V. K. Prasanna, "Disaggregation of behind-the-meter solar generation in presence of energy storage resources," in *2020 IEEE Conference on Technologies for Sustainability (SusTech)*, pp. 1–7, IEEE, 2020.
[35] Sense.com, "Sense solar monitoring," Accessed, February 2022. Available at https://sense.com/solar.
[36] Emporia, "Smart home energy management," Accessed, February 2022. Available at https://www.emporiaenergy.com/how-the-vue-energy-monitor-works.
[37] Eyedro, "Track your solar usage with an eyedro solar energy monitor," Accessed, February 2022. Available at https://eyedro.com/solar-energy-monitor/.
[38] SMA, "Monitoring & control," Accessed, February 2022. Available at https://www.sma-america.com/products/monitoring-control.html.
[39] SoalrEdge, "Monitoring platform," Accessed, February 2022. Available at https://www.solaredge.com/us/products/pv-monitoring#/.
[40] K. Taniguchi, Y. Ogino, and H. Irie, "PWM Technique for Power MOSFET Inverter," *IEEE Transactions on Power Electronics*, vol. 3, no. 3, pp. 328–334, 1988.
[41] L. Rozenblat, "A Grid Tie Inverter for Solar System."
[42] S. Hong and D. Ph, "Harmonics and Noise in Photovoltaic (PV) Inverter and the Mitigation Strategies White Paper," *White Paper*, pp. 1–7.
[43] D. Darmawardana, S. Perera, D. Robinson, and J. Meyer, "Investigation of High Frequency Emissions Photovoltaic Inverters of Different Topologies," *International Conference on Harmonics and Quality of Power (ICHQP)*, 2018.
[44] D. Boroyevich, X. Zhang, H. Bishinoi, R. Burgos, P. Mattavelli, and F. Wang, "Conducted EMI and systems integration," *CIPS 2014 - 8th International Conference on Integrated Power Electronics Systems, Proceedings*, pp. 25–27, 2014.
[45] S. Harb, M. Kedia, H. Zhang, and R. S. Balog, "Microinverter and string inverter grid-connected photovoltaic system — a comprehensive study," in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, pp. 2885–2890, 2013.
[46] S. Deshpande and N. R. Bhasme, "A review of topologies of inverter for grid connected pv systems," in *2017 Innovations in Power and Advanced Computing Technologies (i-PACT)*, pp. 1–6, 2017.
[47] D. Hamza and P. Jain, "Conducted EMI in grid-tied PV system," *INTELEC, International Telecommunications Energy Conference (Proceedings)*, pp. 0–6, 2010.
[48] J. Zhang, X. Ji, Y. Chi, Y.-c. Chen, B. Wang, and W. Xu, "OutletSpy: Cross-outlet Application Inference via Power Factor Correction Signal," in *WiSEC*, pp. 181–191, 2021.
[49] S. Gupta, M. S. Reynolds, and S. N. Patel, "Electrisense: single-point sensing using emi for electrical event detection and classification in the home," in *Proceedings of the 12th ACM international conference on Ubiquitous computing*, pp. 139–148, 2010.
[50] M. Gulati, S. S. Ram, and A. Singh, "An in depth study into using emi signatures for appliance identification," in *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-efficient Buildings*, pp. 70–79, 2014.
[51] B. Ismail, S. Taib, A. M. Saad, M. Isa, and C. Hadzer, "Development of a single phase spwm microcontroller-based inverter," in *2006 IEEE International Power and Energy Conference*, pp. 437–440, IEEE, 2006.
[52] K. Taniguchi, Y. Ogino, and H. Irie, "Pwm technique for power mosfet inverter," *IEEE Transactions on Power Electronics*, vol. 3, no. 3, pp. 328–334, 1988.
[53] T. M. Inc., "Regression learner version: 9.14 (r2023a)," 2023.