



Harvard John A. Paulson
School of Engineering
and Applied Sciences

Workshop on Enabling Cyber-Resilient Distribution Systems with Edge Inverter-Based Resources (IBR)

Exploring Capabilities of Large Language Models at the Grid Edge

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10/19/2024

Professor Participates in White House Roundtable Discussion on Artificial Intelligence for Energy

March 2, 2024 | By Katie Satterlee

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IN THIS STORY



Le Xie



AI for Energy

Opportunities for a Modern Grid and Clean Energy Economy

April 2024

Exploring the capabilities and limitations of large language models in the electric energy sector

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Large language models (LLMs) as ChatBots have drawn remarkable attention thanks to their versatile capability in natural language processing as well as in a wide range of tasks. While there has been great enthusiasm toward adopting such foundational model-based artificial intelligence tools in all sectors possible, the capabilities and limitations of such LLMs in improving the operation of the electric energy sector need to

being explicitly programmed for them. This architecture's scalability and efficiency in capturing long-range dependencies led to the development of generative pre-trained transformer (GPT) models.² Due to their versatility, these LLMs are swiftly finding applications across many sectors, with researchers actively exploring their potential within the electric energy sector. While research has showcased their potential in tasks such as generating customized code,³ utilizing retrieval augmented generation (RAG) capabil-

led to an exponential increase in the volume of equipment/devices and associated data, posing significant challenges for power system operators and utilities who must manage these complexities without a corresponding increase in the accumulation of instantaneous capacity to power system in necessitating date these ne gate their ass

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NEWS

Bringing GPT to the grid

The promise and limitations of large-language models in the energy sector

By [Leah Burrows](#) | [Press contact](#)
June 19, 2024



Much has been discussed about the promise and limitations of large-language models in industries such as education, healthcare and even manufacturing. But what about energy? Could large-language models (LLMs), like those that power ChatGPT, help run and maintain the energy grid?



Outline

- **ChatGPT and Large Language Models Introduction**
- Capabilities & Limitations of LLMs in Power Electronics Circuitry



Large Language Models

- You may have used ChatGPT, but what is it?
Here is ChatGPT's own answer:



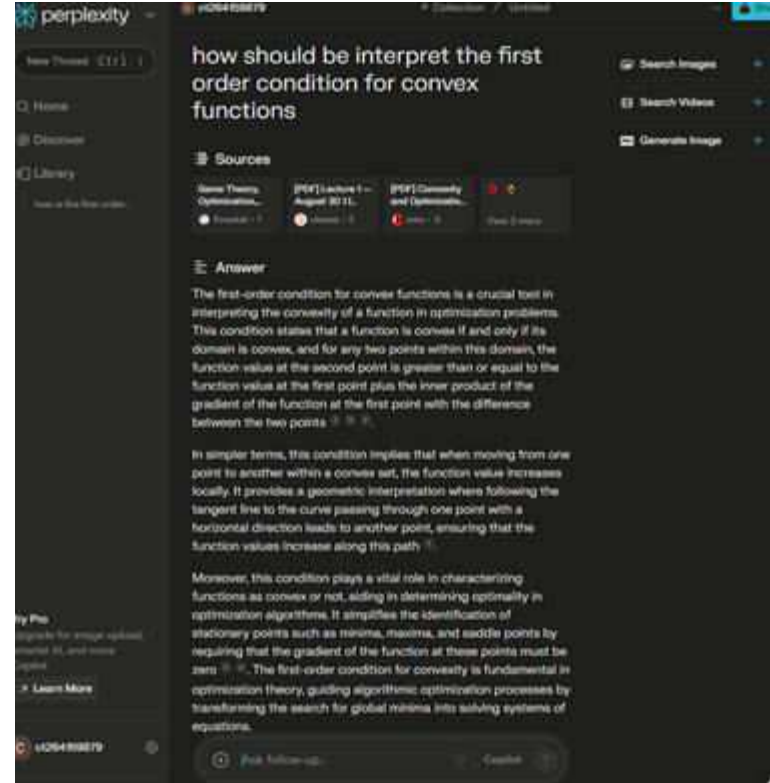
ChatGPT is an artificial intelligence chatbot developed by OpenAI, based on the Generative Pre-trained Transformer (GPT) architecture. It is designed to understand and generate human-like text based on the input it receives, enabling it to converse with users on a wide range of topics. ChatGPT has undergone several iterations, with improvements in its ability to understand context, manage more complex dialogues, and generate more accurate and relevant responses over time.

.....



Large Language Models

- ChatGPT is only one of many existing powerful Large Language Models (LLMs)
 - Gemini (google), Llama3 (meta), Perplexity, Claude (Anthropic), etc.
- Demos of applications in power systems based on LLMs shortly
- Next few slides: key concepts in language models, model structure, capabilities, RLHF, fine-tuning, retrieval augmented generation, safety, OpenAI APIs, and open-source models
- **Note:** the research on LLMs is ongoing, with many aspects not fully understood

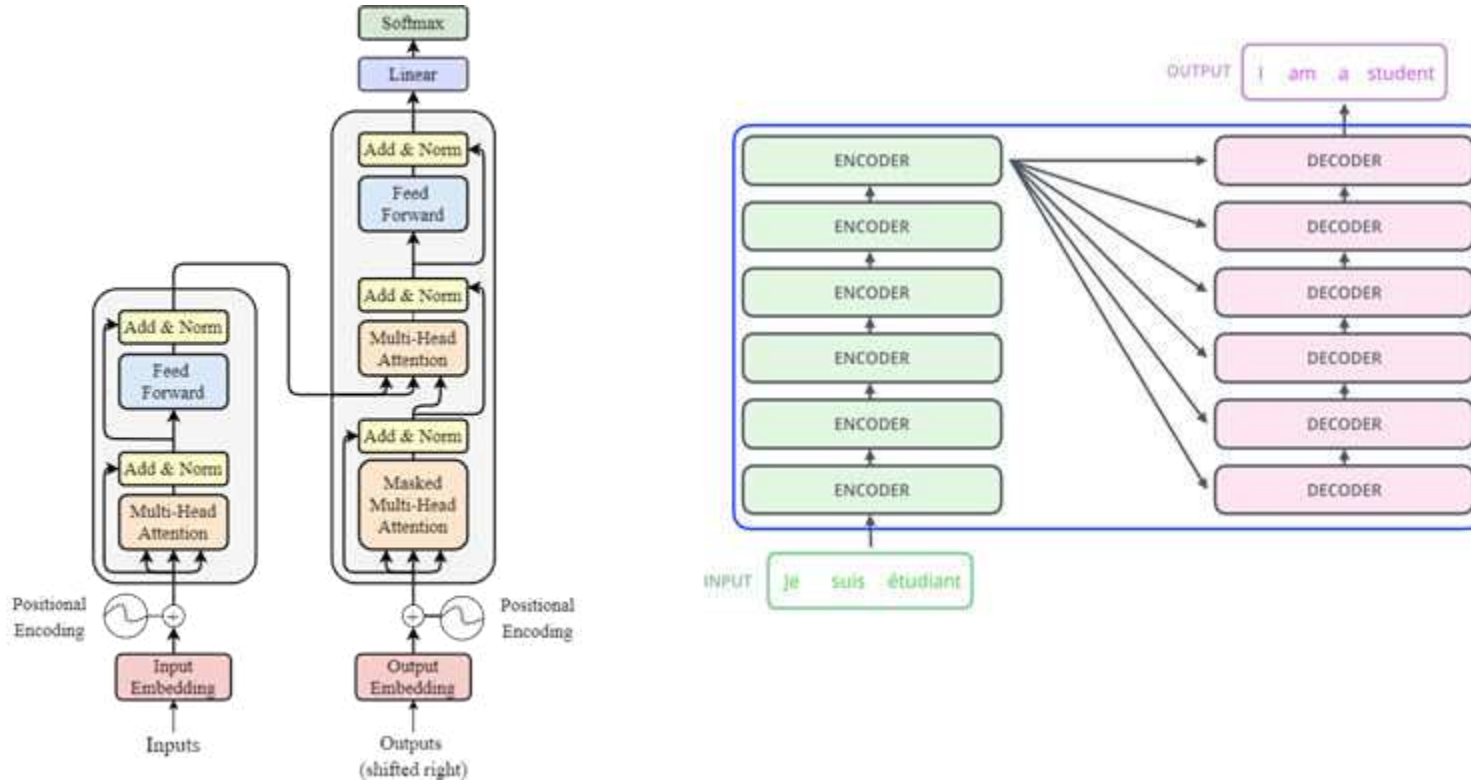


Large Language Models

- Large
 - Very large training data set
 - Very large number of training parameters
- General purpose
 - Common structure of many languages
 - Restriction on computing/storage resources
- Pre-trained and fine tuned



The Transformer Model



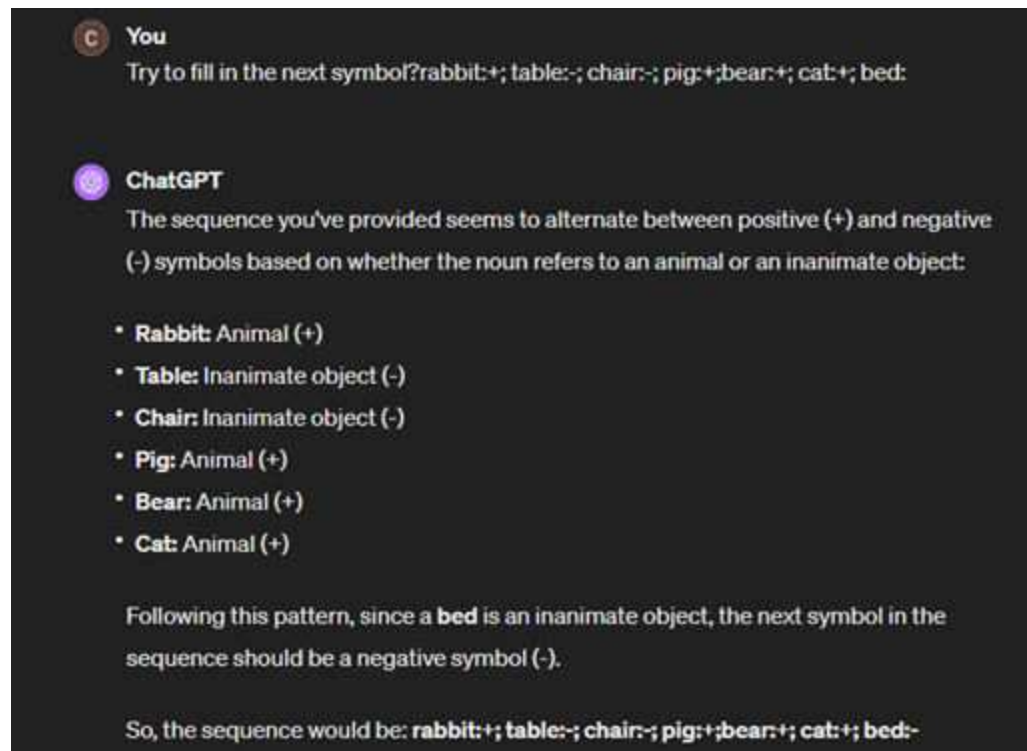
From "Attention is all you need" Vaswani, et al., 2017

Alammar, J (2018). The Illustrated Transformer [Blog post]. Retrieved from <https://jalammar.github.io/illustrated-transformer/>



Emergent Capabilities

- In-weight learning: LLMs appear to “remember” large chunks of texts as answers:
 - Not surprising, given the number of parameters in the models.
- In-context learning: LLMs appear to be able to learn from context.
 - Surprising: No retraining of the model
- Combination: looks like human reasoning capability



Fine-tuning of LLMs

- Fine-tuning with specific data or tasks:
 - Pre-training models are generic: may not have enough training data for a specific task (we don't even know it for foundational models)
 - Use a smaller specialized (supervised) dataset to fine-tune the model for a specific task
 - In contrast to pre-training, fine-tuning is much less expensive
 - Techniques needed to guarantee the fine-tuned model is not too different from the pre-trained model



Open-Source Models

- Hosted service may not satisfy the business need (e.g., privacy)
- In-house models can be built, usually based on open-source LLMs, but not from scratch
 - LLama3, Bert, Falcon 180B, etc.
 - Computation resources required
 - Fine-tuning usually required
 - Further functional components/layers may be needed



Summary of Part I

- LLMs are large transformer models, at least right now
- LLMs show strong capabilities: a combination of in-weight learning vs. in-context learning capabilities
- Fine-tuning, Retrieval-Augmented Generation (RAG), hosted LLM APIs, and open-source models
- Still a new area of development: there are many monetizing opportunities in extending or simply applying these techniques



Outline

- ChatGPT and Large Language Models Introduction
- **Capabilities & Limitations of LLMs in the Power Electronics Circuitry**



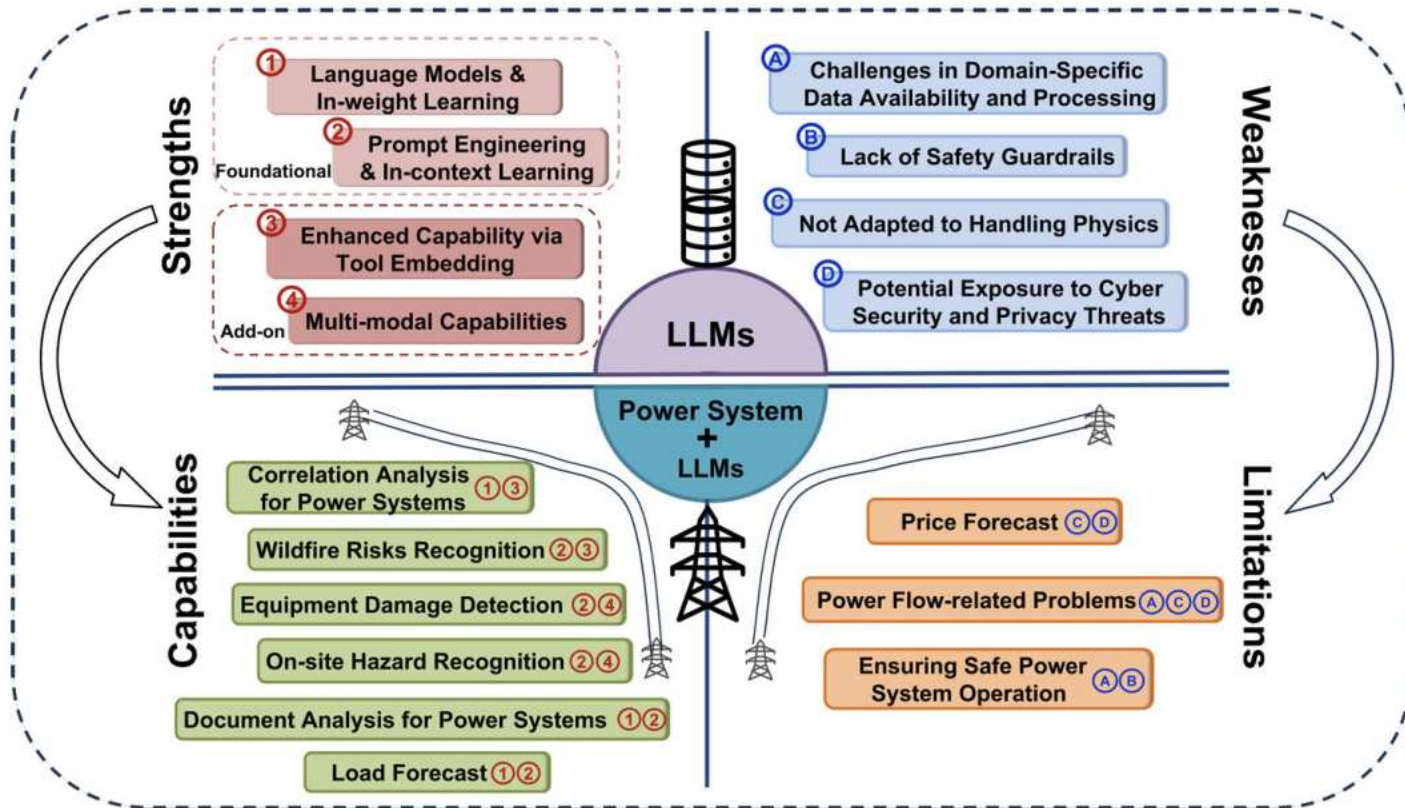
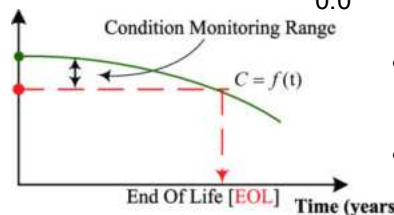
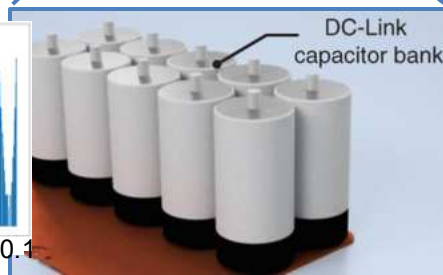
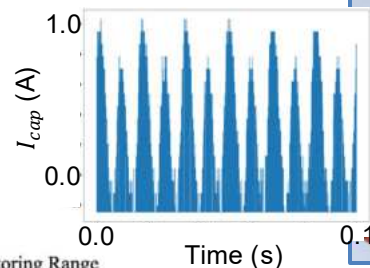
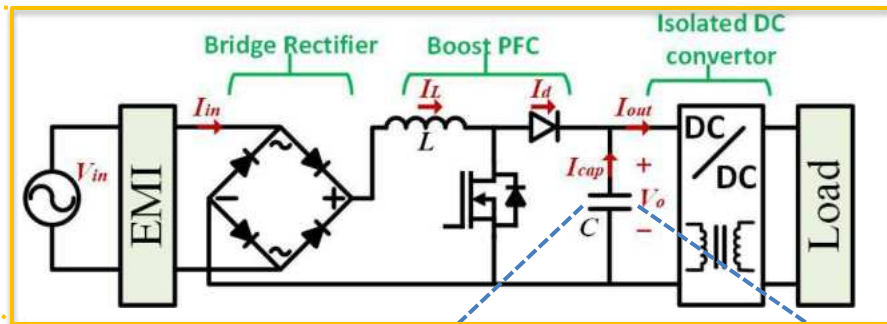
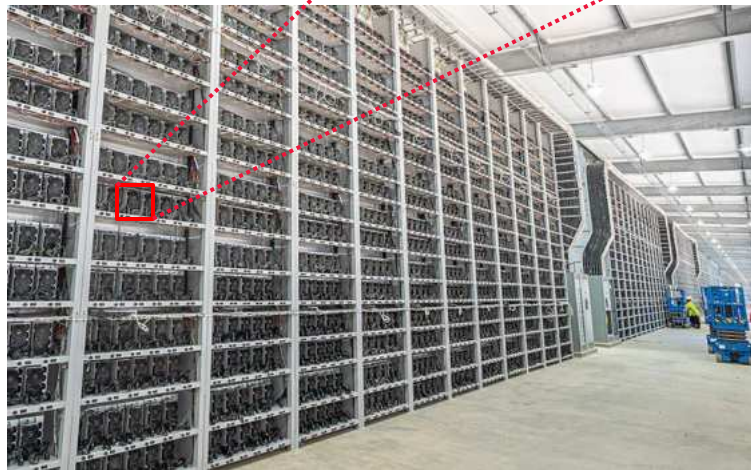


Figure 1: Capabilities and Limitations of Applying LLMs in the Electric Energy Sector



Use Case 3: Estimating DC-Link Capacitor Current Ripple

Power Factor Correction (PFC)



- High ripple \rightarrow More heat \rightarrow Faster capacitor degradation
- Difficult to monitor capacitors individually \rightarrow Can we estimate?

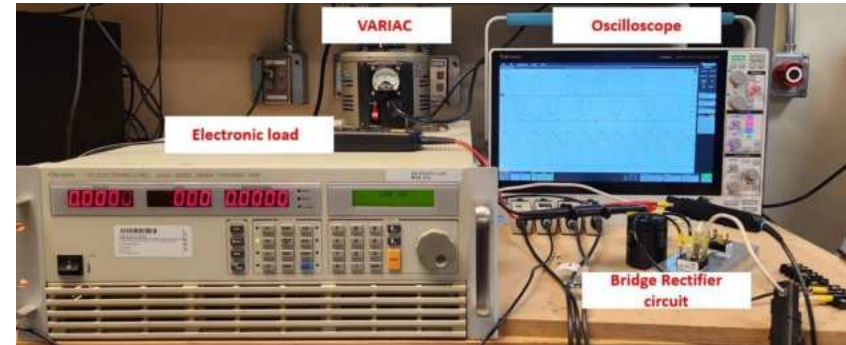
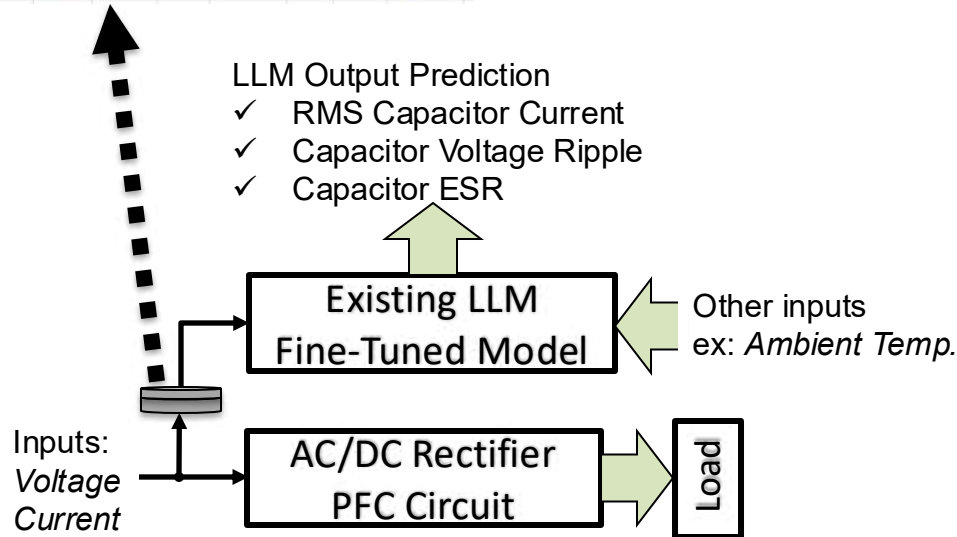


Can we use LLMs?

Key idea: ripple content = $f(\text{load, ambient condition})$

R	V_RMS	V_h2	V_h4	I_RMS	I_h2	I_h4	power
39	143.9	9.837	2.915	6.647	4.37	2.665	956.5033
40	144.3	9.633	2.884	6.535	4.28	2.636	943.0005
41	144.7	9.428	2.847	6.421	4.2	2.603	929.119
42	145.1	9.216	2.802	6.302	4.12	2.57	914.4202
43	145.4	9.042	2.769	6.194	4.04	2.533	900.6076
44	145.7	8.851	2.732	6.073	3.96	2.5	884.8361
45	146.1	8.679	2.695	5.989	3.89	2.469	874.9929
46	146.5	8.511	2.655	5.881	3.82	2.436	861.5665

Experimental Data



Can we use LLMs?

R	V_RMS	V_h2	V_h4	I_RMS	I_h2	I_h4	power
39	143.9	9.837	2.915	6.647	4.37	2.665	956.5033
40	144.3	9.633	2.884	6.535	4.28	2.636	943.0005
41	144.7	9.428	2.847	6.421	4.2	2.603	929.119
42	145.1	9.236	2.81	6.307	4.11	2.575	914.4202
43	145.4	9.042	2.769	6.194	4.04	2.533	900.6076
44	145.7	8.851	2.732	6.073	3.96	2.5	884.8361
45	146.1	8.679	2.695	5.989	3.89	2.469	874.9929
46	146.5	8.511	2.655	5.881	3.82	2.436	861.5665

Experimental Data

Direct prompting:

For a load of 564 W, the DC-bus capacitor RMS current, the second harmonic and the fourth harmonic components are 3.66A, 2.28A, and 1.62A, respectively, for a bridge rectifier. Calculate DC-bus capacitor RMS current, the second harmonic and the fourth harmonic components given the load is 710 W. *Just provide me the final solution*

For a load of 710 W, the final solutions are:

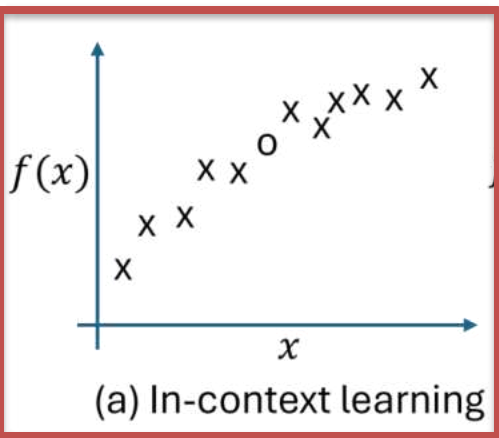
- DC-bus capacitor RMS current: 4.60 A
- Second harmonic component: 2.87 A
- Fourth harmonic component: 2.04 A

Context of Power Electronics Hinders
LLMs ability to estimate



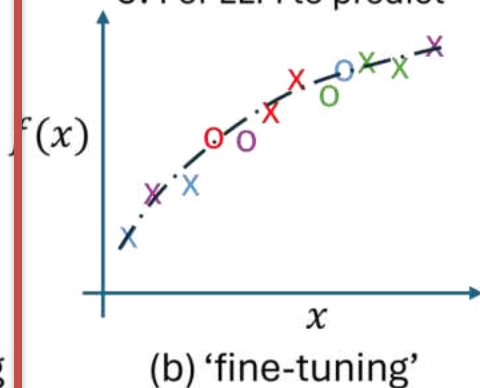
Can we use LLMs?

Key idea: Pose the problem as *unknown function mapping* problem



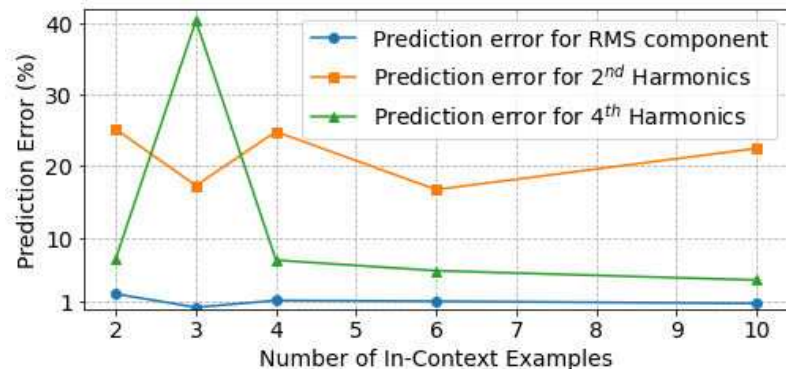
X: Provided as examples

O: For LLM to predict

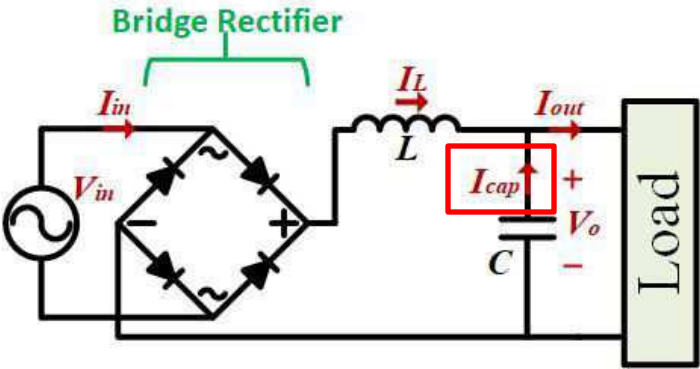


```
model="gpt-3.5-turbo-0125",
messages=[
  {
    "role": "user",
    "content": "Here is an example of value mapped from x to y, z and w:
x: 590, y: 3.9, z: 2.4, w: 1.7
Here is another example of values mapped from x to y, z and w:
x: 700, y: 4.7, z: 3.0, w: 2.0
Here is the unknown x
x: 650
The value of y, z and w corresponding to unknown x are:"
  }
],
```

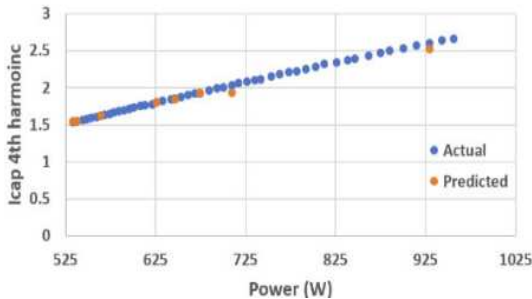
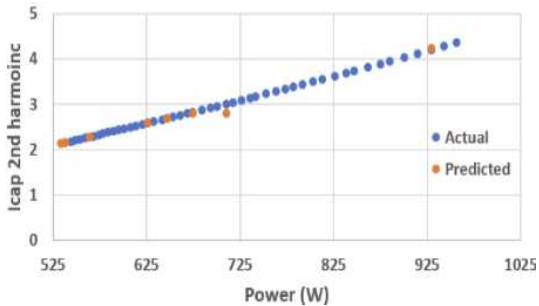
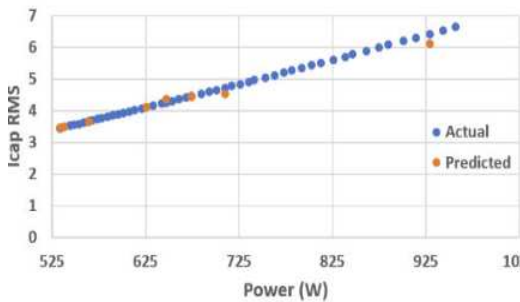
In-Context Learning:



Estimating Capacitor Current Ripple with fine-tuning : Bridge Rectifier



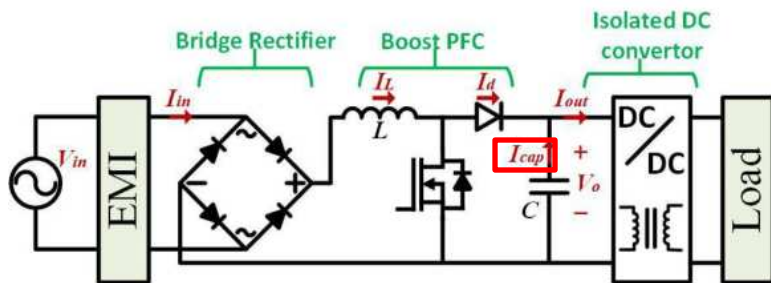
● LLM predicted
● Measured data



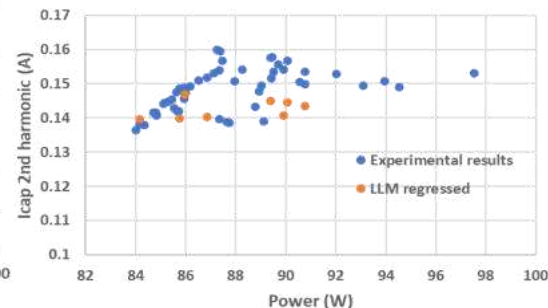
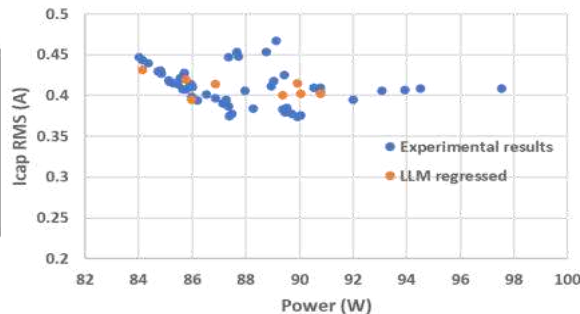
Power (W)	I_{cap} RMS (%)	I_{cap} 2nd Harmonic (%)	I_{cap} 4th Harmonic (%)
533	0.49	0.53	0.64
538	0.19	0.07	0.05
564	0.17	0.33	0.37
626	0.06	0.31	0.06
646	2.82	0.13	0.72
674	0.28	0.95	0.58
710	3.83	6.4	4.96
929	4.91	0.83	3.05



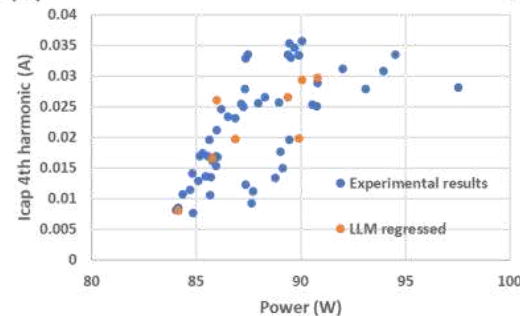
Estimating Capacitor Current Ripple with fine-tuning: PFC Circuit



- LLM predicted
- Measured data



Power (W)	Icap RMS (%)	Icap 2 nd Harmonic (%)	Icap 4 th Harmonic (%)
84.15	2.23	0.35	5.47
85.77	4.05	5.15	2.25
85.97	4.74	3.70	7.04
86.85	2.36	3.90	14.15
89.38	5.93	8.11	20.82
89.91	5.18	1.16	22.06
90.06	6.28	7.19	17.72
90.78	0.04	1.46	3.03



$$APE = \frac{|Actual Value - Predicted Value|}{|Actual Value|} \times 100\%$$



Use Case 4: Equipment Damage Detection

- Zero-Shot Prompting



Classify



You

We classify an insulator faulty, if there is discoloration, chip or scratch. Is this insulator faulty or intact?



ChatGPT

The image you've provided shows a high-voltage insulator typically used on electric power transmission lines. Upon examining the image, I don't see any obvious signs of discoloration, chips, or scratches that would indicate it is faulty. The insulator appears to be intact, with no visible damage to the individual discs or the overall structure.

Wrong classification!



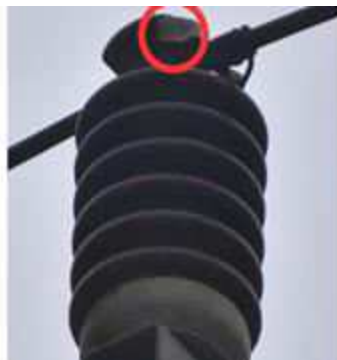
Use Case 4: Equipment Damage Detection

- Few-shot Prompting



Small scratch, Status: Failure

In-context Learning Process



Broken Head, Status: Failure



Broken Layer, Status: Failure



Use Case 4: Equipment Damage Detection



Visible dark mark, which may indicate defect.

Classify



Insulator appear intact

Dataset	Accuracy(%)
Overall Accuracy	80
Only Intact Insulator	85
Only Faulty Insulator	70



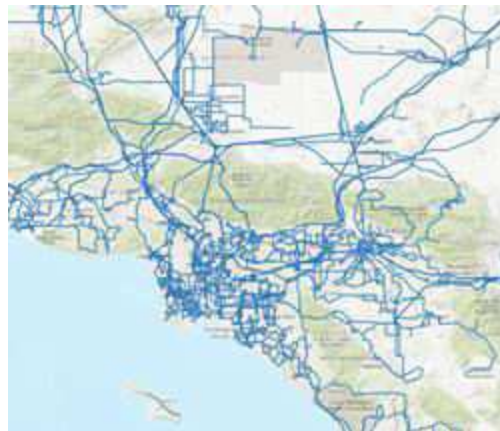
Use Case 5: Wildfire Hazard Analysis & Visualization

Wildfire historical
map

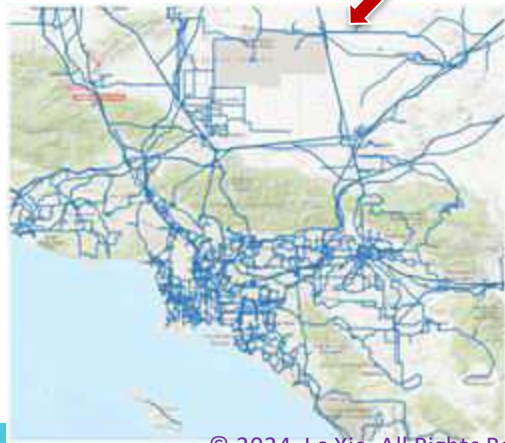


Which transmission Line
should I pay attention to
wildfire hazard?

Transmission Line
map



Highlight in red
on the map



The transmission lines that require close attention have been highlighted in red on the map, considering the historical wildfire data and their locations:

1. **In the vicinity of Angeles National Forest:** These lines are at a higher risk due to their proximity to a region with a history of wildfires, especially recent ones.
2. **Near Santa Clarita:** Given the recent wildfires in the 2010s, the transmission lines in this area are potentially vulnerable.
3. **Between Los Angeles and Riverside:** This urban corridor is critical, and any transmission lines within it need to be closely monitored due to the high impact any disruption could cause.

The map with the highlighted transmission lines can be downloaded from the link below:

[Download the annotated transmission line map \[6-\]](#)

Use Case 5: Wildfire Hazard Analysis & Visualization



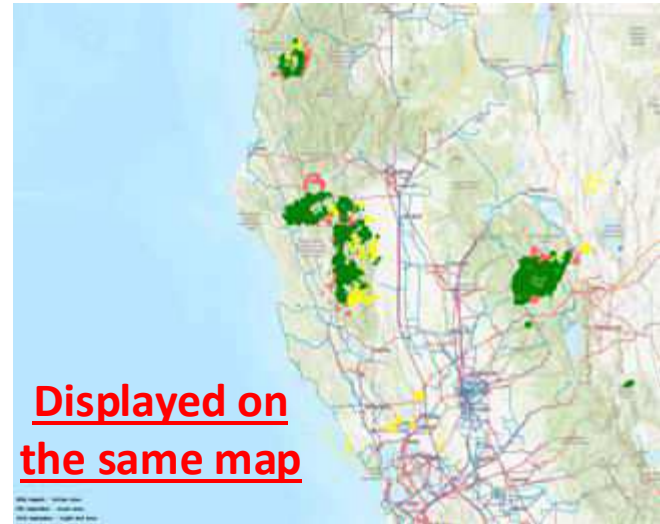
August



September



October



Possibility for close-loop control?

WIRED

SECURITY POLITICS GEAR THE BIG STORY BUSINESS SCIENCE CULTURE IDEAS MERCH

SIGN IN

WILL KNIGHT

BUSINESS SEP 12, 2024 1:05 PM

OpenAI Announces a New AI Model, Code-Named Strawberry, That Solves Difficult Problems Step by Step

The ChatGPT maker reveals details of what's officially known as OpenAI o1, which shows that AI needs more than scale to advance.



The role of electric grid research in addressing climate change

Received: 13 March 2024

Accepted: 3 July 2024

Le Xie^{1,2}✉, Subir Majumder¹, Tong Huang³, Qian Zhang¹,
Ping Chang⁴, David J. Hill⁵ & Mohammad Shahidehpour⁶

<https://doi.org/10.1038/s44287-024-00083-0>

Sustainable electrification in the era of AI

Le Xie, Na Li & H. Vincent Poor

 Check for updates

Sustainable electrification is essential for addressing climate change and leveraging artificial intelligence (AI). Electric grids have a fundamental role in decarbonizing the economy and enabling AI. Here we propose a comprehensive research agenda that integrates innovations in material discovery, computer architecture, smart grids and system theory to accelerate efficient, large-scale, low-carbon electrification.

With the increasing decarbonization in various sectors through electrification, alongside growing computing demands in artificial intelligence (AI), cryptocurrency mining, and internet data centres, electricity consumption in major economies is likely to double by 2050¹. This growth is about ten times higher than that registered during the same period of growth between the 1990s and 2020s. In the USA, more than one-third of the increase in electricity demand by 2026 is projected to

and markets for power grids that are well aligned with climate goals are required². AI models could assist in the decision making on several levels from planning to operation and control³.

Fourth, as the reliance on advanced computing and AI continues to gain criticality, safeguarding power grids against potential disruptions (natural⁴ or manmade⁵) and vulnerabilities becomes increasingly important.

A full-stack research agenda

To resolve the dual challenges of sustainable electrification, first we need to re-imagine how the electrical energy network is built and operated, and subsequently we need to investigate how to optimize AI (Table 1).

A research agenda needs to be planned to develop electric grids that can deliver low-carbon energy resources to an increasing level of electrified demand. In this regard, we highlight three distinct research needs. The first crucial area of investigation addresses the development of more energy-efficient conversion materials, as reported by the US Office of Energy Efficiency and Renewable Energy, that can enhance the efficiency of energy processing devices (such as wind and solar inverters) and provide long-term storage solutions⁶. AI could help to accelerate the discovery of materials in this direction⁷.

Summary

- LLM for Power
 - Opportunities: Co-pilot for time-sensitive advisory roles
 - Challenges: Safety guardrail and data privacy
- Beginning of this new era, and this community has an important role to play in providing the *domain knowledge-based “guardrail”*.



Thanks!



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