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Designing for scale: Transformer design strategies for a sustainable global growth of Data Centers

Hitachi Energy

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Valentina Valori has over 20 years of experience in the Power Transformer industry acquired in Hitachi Energy (formerly ABB). She holds a master's degree in electrical engineering from Padua University and MBA-SDA from Milan Bocconi University, in Italy. Her expertise spans electrical power transformer design engineering, project management, R&D, and global marketing, with a strong track record of leading multicultural teams. Certified in Lean 6SIGMA and CSPO (Scrum Product Ownership), she is committed to quality and efficiency. Valentina is today responsible for shaping Power Transformer product strategy to support standardization and innovation towards a more sustainable world.

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As Regional Product Manager at Hitachi Energy, Alex leads the roadmap for the small and medium power transformer portfolio, with a focus on the growing data center sector. He translates customer needs into forward-looking solutions that enhance infrastructure resilience and energy efficiency across the region.

Contents

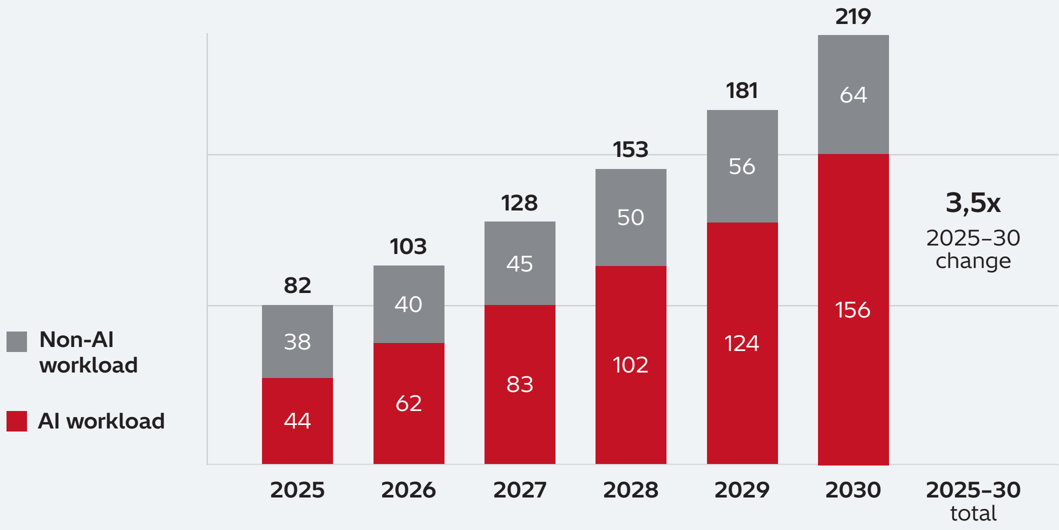
1 Introduction

The global data center industry is undergoing explosive growth, driven by the accelerating adoption of artificial intelligence (AI), cloud computing, and digital services. However, this rapid expansion is increasingly constrained by critical infrastructure challenges, most notably, limited power availability and long lead times for essential components like power transformers. These bottlenecks are straining utilities' ability to deliver reliable power and threatening to delay the development of infrastructure vital to the digital economy.

According to McKinsey, global data center capacity is projected to reach 219 GW by 2030—nearly triple the 82 GW estimated for 2025. While McKinsey does not specify the exact regional breakdown, industry benchmarks suggest that the United States could account for approximately 40–45% of this total. That implies a U.S. capacity of roughly 88–98 GW by 2030. AI workload alone will account for over 70% of this demand, growing 3.5 times over the same period.

Both AI and non-AI workloads will be key drivers of global data center capacity demand growth through 2030.

Estimated global data center capacity demand, "continued momentum' scenario, gigawatts.



Incremental AI capacity added per year, gigawatts	13	18	21	19	22	31	124

Note: Figures may not sum to totals, because of rounding.

Source: Garther reports; IDC reports; Nvidia capital markets reports; McKinsey data Center Demand Model

Image source: Data center demands

Grid constraints have emerged as the top barrier to data center development. Average utility connection wait times now exceed four years, with some regions facing delays of up to a decade. The rise of generative AI has intensified power requirements, with hyperscale facilities demanding hundreds of megawatts of capacity and rack densities surpassing 100 kW.

To meet these demands, developers are increasingly targeting regions with more favorable power availability. This shift is reshaping infrastructure strategies, particularly in the specification of high-voltage transformers (220 kV-500 kV) and large MVA-rated units (150–250 MVA) to support multi-megawatt loads per data hall.

However, custom-built transformers—often required for these applications—face lead times of 2–4 years, compounding supply chain pressures. Early procurement and close collaboration with OEMs are now essential.

To address these challenges and unlock the next wave of digital infrastructure, stakeholders must:

- Scale up production and reduce lead times for critical components.
- Alleviate supply chain bottlenecks for strategic transformer components.
- Enhance flexibility to unlock access to global manufacturing capacity.

Additionally, technical specifications—such as voltage class, on-load tap changers, vector group configurations, tertiary windings, and grounding practices—must be tailored to regional grid conditions.

2 Transmission grids global practices

2.1 Regional overview

2.1.1 North America

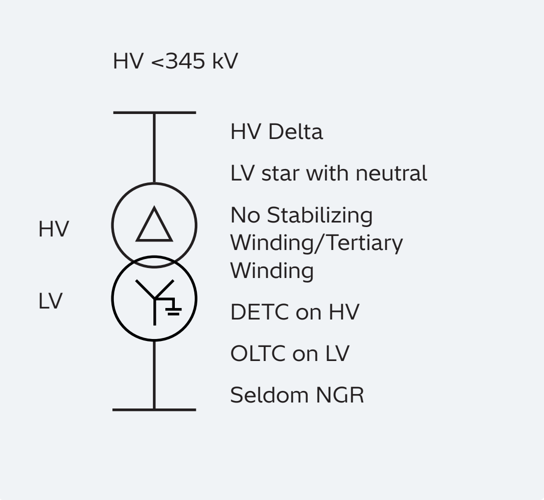
High voltage transmission in North America operates at several voltage levels including 115 kV, 138 kV, 161 kV, 230 kV, 345 kV, 500 kV, and 765 kV. Most installed infrastructure today operates at 115 kV to 230 kV[1], with notably large-scale buildouts of 345 kV, 500 kV, and 765 kV expected over the next decade.

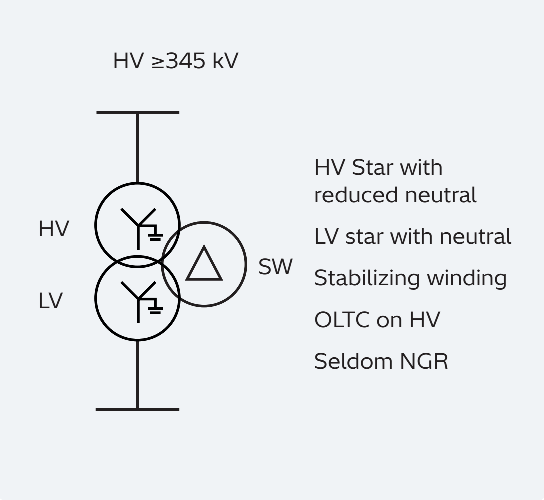
A multitude of transformer vector group types exist in North America's grid. On the high-voltage (HV) winding of the transformer, a Delta (D) connection is the most common practice up to 345 kV, and the low-voltage (LV) winding is most constructed using a Wye or Star with neutral (yn) connection type.

Some data center customers have recently explored a Y or YN connection type for windings handling 345 kV and above, so a more popular vector group in this scenario is "YNyn0+d". The pros and cons of different 345 kV transformer solutions are addressed later in this article.

This construction utilizes a stabilizing (or buried delta winding without any load), to stabilize the system and reduce harmonic distortion. More information on this winding is contained in the next section 7.1.2.

When considering grounding of the transformer, it is common practice to ground the LV neutral to stabilize the voltage during unbalanced load conditions and provide clear path for fault currents. Additionally, some users opt to ground the neutral through a Neutral Grounding Resistor (NGR) with the intent to reduce short circuit currents to the ground. A typical specification may require the NGR to withstand 400A or 800A for 10 seconds.



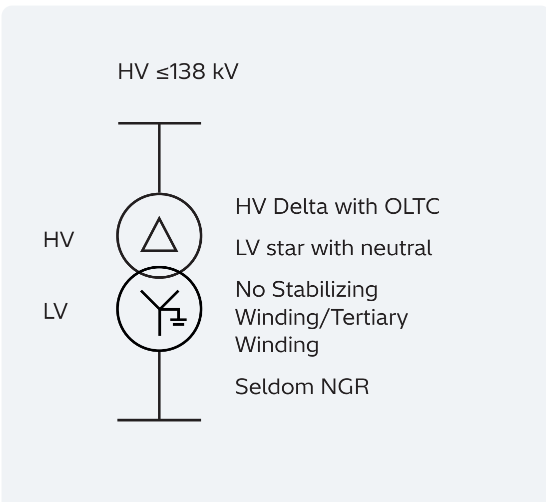


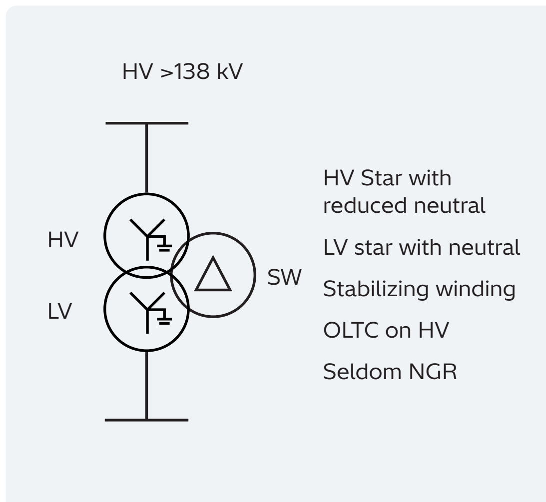
2.1.2 Latin America

Latin America's grid infrastructure high-voltage transmission lines operate at many voltages including 110 kV, 115 kV, 138 kV, 220 kV, 230 kV, 345 kV, 430 kV, 440 kV, 500 kV, and 750 kV. By far the most common across major markets, like Brazil and Colombia for example, are 220-230 kV and 500 kV.[2][3] In Mexico, 230 kV and 400 kV lines constitute more than 50% of the total transmission length.[4]

When it comes to transformer connection types, YN is primarily used on the HV side, and the LV side is connected as yn or d. Some transformers on the lower end of the HV range, i.e. 110-138 kV, can be seen using Dyn connections.

As for the usage of stabilizing windings, they are commonly used when the transformer has a YNyn vector group.



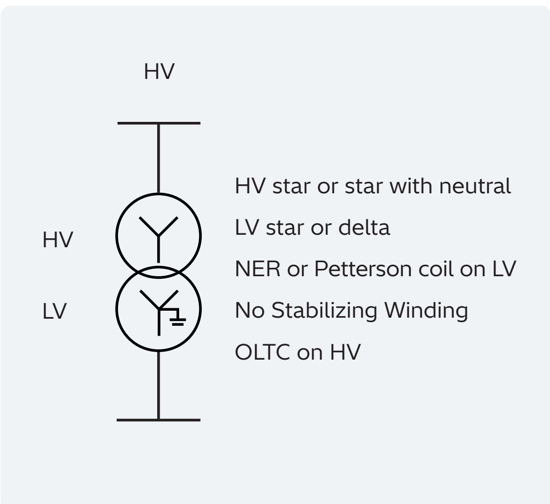


2.1.3 Europe

High voltage sub-transmission and transmission European network operators[5] work at several voltage levels including 132 kV, 150 kV, 220 kV, 380 kV, and 400 kV. Most installed Transmission Systems operate today mainly at 220 kV and 380-400 kV. 750 kV is also present in some specific Balkan and Soviet regions but it is not the common practice in the European continent.

Typical transformer connection on HV side is Star with or without neutral brought out, LV side is normally delta or star depending on the application, most of the utilities operate LV normally star with neutral grounded via NER or Pettersen coil.

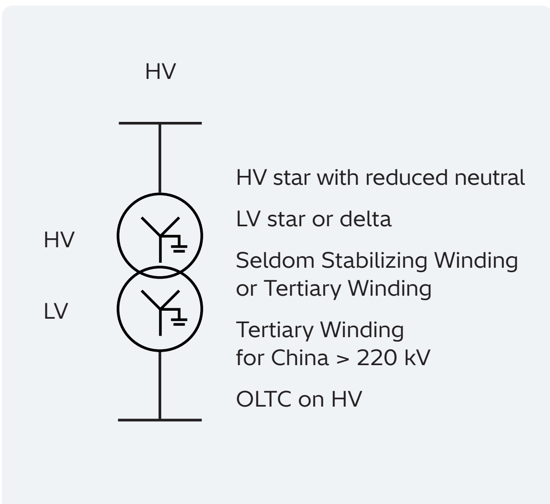
The usage of a stabilizing winding has become a less common practice as it's considered a potentially weak part of the transformer, adding more complexity and risk than actual benefits to the overall system.



2.1.4 Asia

High voltage transmission Asian network operators work at several alternating voltage levels including 110-132 kV, 220 kV, 380 kV, 400 kV & 765 kV. India's 765 kV transmission line is also connecting western & southern region (e.g. warora-kurnool) and western and northern regions (e.g. vindhyachal-varanasi). China utilizes a variety of transmission voltages in its power grid, including 110 kV, 220 kV, 330 kV, 500 kV, 750 kV, and 1000 kV for AC transmission.

Transformer installed capacity in China are normally two windings units having HV side connected as star with reduced grounded neutral, YN, and LV side connected as delta, without stabilizing/tertiary winding because of course not needed. However, utilities in China also have tertiary windings for HV >220 kV. While transformer installed capacity in India normally has two windings units till 200MVA power



capacity, having HV side connected as star with reduced solidly grounded neutral, YN, while LV side connected as star with fully insulated neutral again solidly grounded, since rarely NGR is adopted. Tertiary winding in India is used for higher power rating (>200MVA), mostly as stabilized purpose. These practices are in-line with published guidelines of Central Electricity Authority (CEA), Government of India[6].

Majority of installed transformer bases have OLTC on HV side of the transformer providing constant LV voltage with constant flux voltage variation (CFVV, chapter 7.1.1).

Overall, AC power grid interconnections in Asia[7] could be divided into the following networks:

- South and South-West Asia are mainly transmission lines that include 110-132 kV, 220 kV and 400 kV voltage levels.
- South-East Asia are transmission networks that include 110-138 kV, 230-275 kV and 500 kV transmission lines.
- East and North-East Asia are mainly transmission network between the Russian Federation and China that currently includes 110, 220 and 500 kV transmission lines.
- North and Central Asia are all transmission at 220 kV, 300 kV and 500 kV AC voltage lines.

Typical transformer connection on HV side is Star with neutral brought out, reduced insulation level and grounded; LV side is normally star but could be rarely also delta, depending on the application; when star-star connection group is chosen, stabilizing winding is sometimes required.

3 Energy demand and capacity challenges

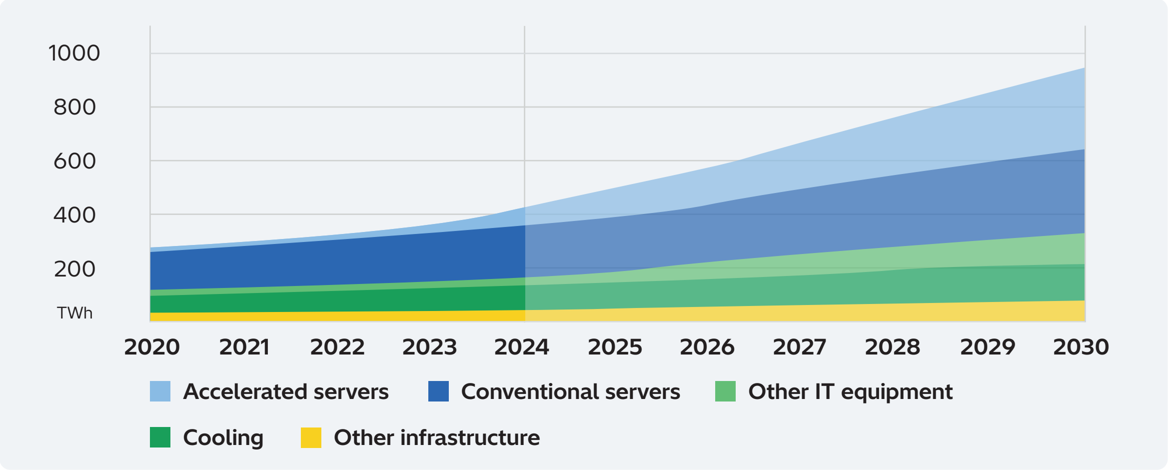
Global energy demand is rising at an unprecedented pace, driven by the rapid expansion of data centers and the integration of renewable energy sources. In response, utilities are ramping up capital expenditures to build new transmission lines and power generation facilities. At the heart of this transformation lies the power transformer—a strategic component essential for delivering electricity to millions of consumers.

As demand intensifies, so does the need for faster lead times and increased capacity in transformer systems. The entire supply chain, including critical subcomponents such as bushings, tap changers, preventive auto transformers, and boosters, plays a pivotal role in determining lead times, optimizing footprint, and managing transportation costs.

According to the International Energy Agency (IEA), data centers consumed approximately 415 terawatt-hours (TWh) of electricity in 2024—around 1.5% of global consumption, growing at an average rate of 12% annually over the past five years. While data centers can be built and operational within two years, the broader energy infrastructure requires significantly longer timelines, involving complex planning, extended construction periods, and substantial upfront investment.

Looking ahead, the IEA projects that global electricity consumption by data centers will more than double by 2030, reaching approximately 945 TWh—just under 3% of global electricity use. In the U.S., the growth is even more pronounced. Data centers consumed around 180 TWh in 2024, accounting for nearly 45% of global data center electricity use and over 4% of total U.S. electricity demand. By 2030, this figure is expected to rise by 240 TWh—an increase of 130%—with data centers projected to consume more electricity than the combined total used for producing aluminum, steel, cement, chemicals, and all other energy-intensive goods. By then, data centers will represent 8% of total U.S. electricity consumption and nearly half of the country's electricity demand growth between 2024 and 2030.

This surge is largely fueled by the energy-intensive demands of artificial intelligence (AI), particularly in model training and deployment. Without substantial investment in transmission infrastructure, up to 20% of planned data center projects could face delays, underscoring the urgent need for coordinated action across the energy and technology sectors.



Energy demand from AI – Analysis IEA

4 Implications for data centers in a carbon-constrained world: The relevance and challenge of GHG Scope 3 emissions

Because of the vast amount of electricity consumed in data centers, the International Energy Agen-cy estimates that data centers and data transmission networks each account for approximately 1.5% of global electricity consumption. In 2020, they were responsible for around 330 megatons of CO_2 equivalent, representing 6% of total global GHG emissions and nearly 1% of energy-related emissions[9]. The composition of Scope 1, 2, and 3 emissions in a data center's total GHG inventory varies over its lifecycle[10]:

- Scope 1 (direct emissions): typically 0.2–0.5%.
- Scope 2 (purchased electricity): 31–61%.
- Scope 3 (indirect value chain emissions): 38–69%.

As data centers increasingly transition to renewable and zero-carbon electricity, Scope 2 emissions decline, causing Scope 3 emissions to represent a larger share—up to 99% in facilities powered al-most entirely by clean energy (e.g., Meta's data centers[11]). This wide range reflects the complexi-ty and variability in data center design and operation. The share of Scope 3 emissions depends on several factors:

- Size and architectural design of the data center.
- Type of energy used (renewable vs. fossil-based).
- IT equipment configuration and lifecycle.
- Construction materials and methods.

The main contributors to Scope 3 emissions include:

- Purchased capital goods (e.g., IT and power equipment, and especially transformers being among the most material-intensive power equipment).
- Goods and services.
- Fuel- and energy-related activities.

With rising demand for capacity—driven by both AI and non-AI workloads—Scope 3 emissions are increasing due to intensified construction and expansion of power infrastructure. In response, many leading data center operators are implementing comprehensive Scope 3 GHG programs, focusing on supply chain collaboration to meet their ambitious climate goals and advance toward carbon neutrality and net-zero emissions.

5 Addressing the surge in energy demand

5.1 Foreword

Hitachi Energy has conducted a comprehensive evaluation of alternative solutions to address the evolving challenges faced by utilities and data center operators worldwide. These challenges increasingly demand:

- Higher capacity including Power (VA) and Voltage Class (kV).
- Shorter manufacturing lead times.
- Competitive and standardized solutions.
- Enhanced sustainability through Scope 3 emissions reduction and Life Cycle Assessment (LCA) insights.

This section presents two representative power transformer rating scenarios commonly requested by global data center operators. It explores alternative solutions, objectively assessing their advantages and trade-offs. The analysis offers valuable insights into capacity optimization while supporting our customers and suppliers in advancing their sustainability goals across the value chain.

5.2 Power Transformer analysis

The transformers analyzed are two different real cases coming from our Data Center customers. Both cases have been designed and prepared considering proven practices across the globe as well as typical customers' actual needs and requests.

Hitachi Energy proposed solutions for both cases to simplify the design approach by considering High Voltage (HV) regulation with resistor type On-load tap changer (OLTC) and removing other accessories such as De-energized tap changer (DETC), Preventive Auto transformer (PA) and booster transformers. Those proposed solutions also operate at constant flux voltage variation, the same as the original designs.

Let's look at the analysis and comparison done in following chapters 5.2.1 and 5.2.2.

5.2.1 Case #1 – 120MVA, 138/34.5 kV, ester fluid

The original customer requirements ask for design solution with delta connected high voltage (138 kV) with de-energized tap changer (DETC), on load regulation through On Load Tap Changer (reactor type OLTC) on LV side, operated at constant flux voltage variation (CFVV - 7.1.1). Reactive tap changer as known requires addition of internal preventive auto transformers (PA), installed in the same transformer tank.

The proposed solution is mainly just removing DETC, PA and adding OLTC on HV side. Main rating data differences are summarized in the following Table 1.

120 MVA, 138 /34.5 kV Power Transformer				
	Original Design – 1A		**Proposed Solution – 1B**	
Parameters	HV	LV	HV	LV
Power, MVA	72.3/ 96/ 120MVA		72.3/ 96/ 120MVA	
Voltage, kV	138	34.5	138	34.5
Vector group	Dyn1		Dyn1	
Regulation type	CFVV – Constant Flux		CFVV – Constant Flux	
Tap changer	HV reg: Off Load	LV reg: On Load	HV reg: On Load	LV reg: None
Tap range	±2 x 2.5% (±5%) 144.9 kV to 131.2 kV	±16 x 0.625% (±10%) 37.95 kV to 31.05 kV	±8 x 2.5% (±10%) 151.8 kV to 124.2 kV	N/A
Other Details	IEEE Standard, 60Hz, Natural ester oil, same performance (NLL, LL, BIL, Impedance, Temperature rise)			

Table 1 - Case #1, Designs comparison table

5.2.1.1 Comparative results

Figure 1 and Figure 2 show the 3D view model for the original and proposed solution.

The original solution has accessories such as DETC, PA above OLTC, that require quite high internal space, higher tank and oil.

It is quite visual as the original solution has additional accessories than proposed alternative; from material cost perspective as well, it's clear that proposed solution offers quite competitive cost along with lower footprints and weights.

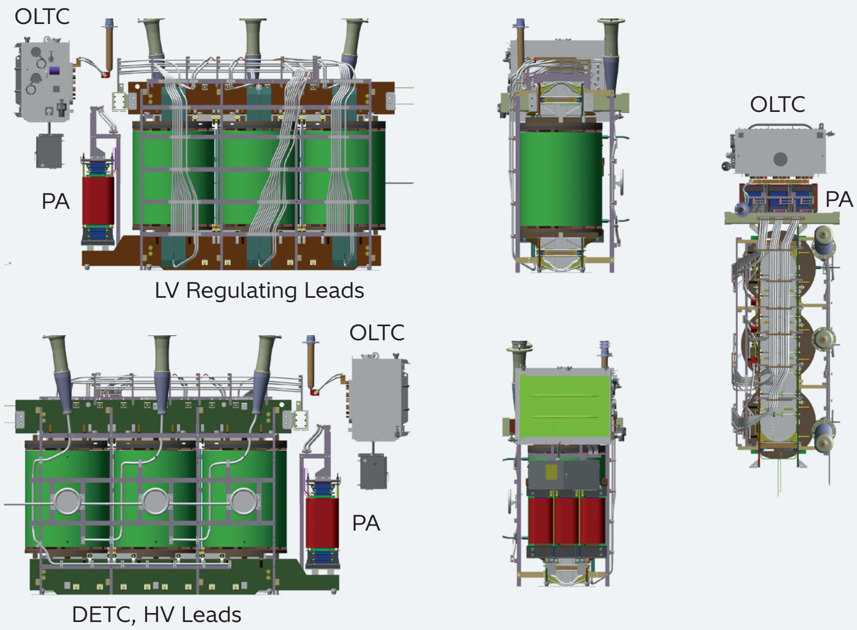
Proposed solution also brings advantages in reducing dependencies on specific suppliers such as reactive type tap changer, preventive auto and booster transformers that are few and niche today in the market, providing lead time reduction for early delivery.

Lesser weight of proposed solution also brings easy handling and management with reduced transportation cost. Moreover, this also bring value reducing complexity of existing solution, opening door of footprint flexibility and efficient management thru' monitoring system.

Case Study – 120MVA

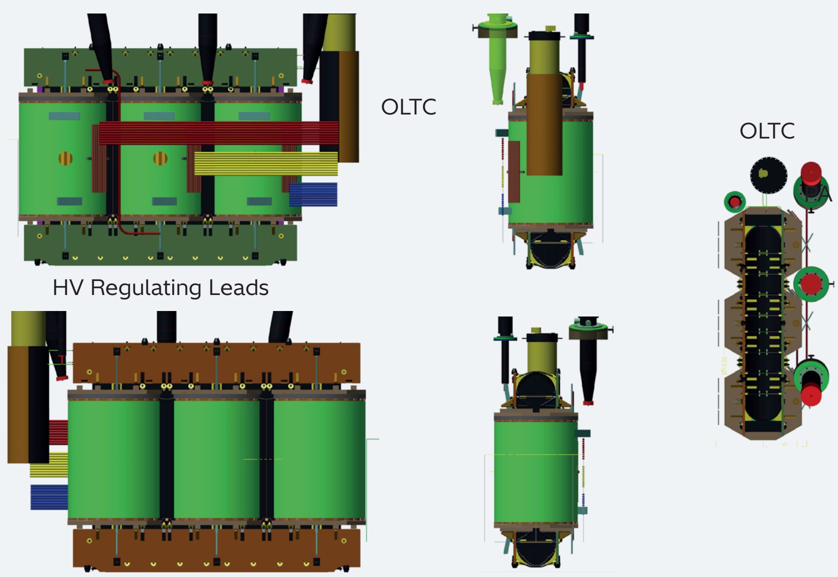
Case #1 – 120MVA, 138/34.5 kV, Power Transformer

Original Design – 1A [OLTC+DETC+PA]



- Regulation bunch on LV, HV and top of unit, complex lead routing
- Accessories [OLTC + DETC + PA + Bushings]

Proposed Solution – 1B [OLTC]



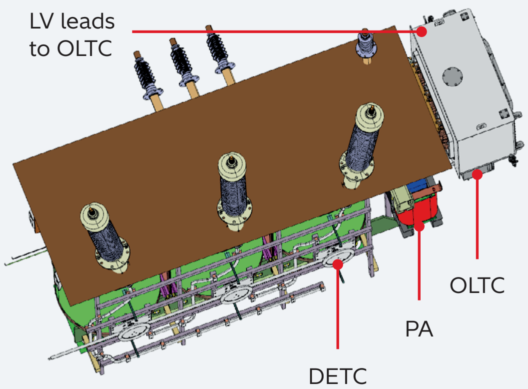
- Regulation bunch on HV side only
- Accessories [OLTC + Bushings]

Figure 1 – Case #1, Comparative designs assembly

Case #1: 120 MVA, 138/34.5 kV, Power Transformer

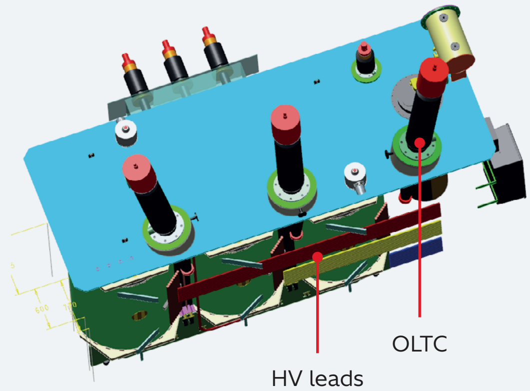
Original design-1A

[OLTC+DETC+PA]



Proposed solution-1B

[OLTC]



Dimmension [mm]	Original design-1A	Proposed solution-1B	Benefit
Length	8,400	8,100	-4%
Width	6,000	6,000	0%
Height	7,300	6,500	-11%

Weight [kg]	Original design-1A	Proposed solution-1B	Benefit
Oil mass	35,000	30,000	-14%
Transport mass	75,000	69,000	-8%
Total mass	126,000	114,000	-9%

Figure 2 - Case#1, Comparative design assembly and footprint

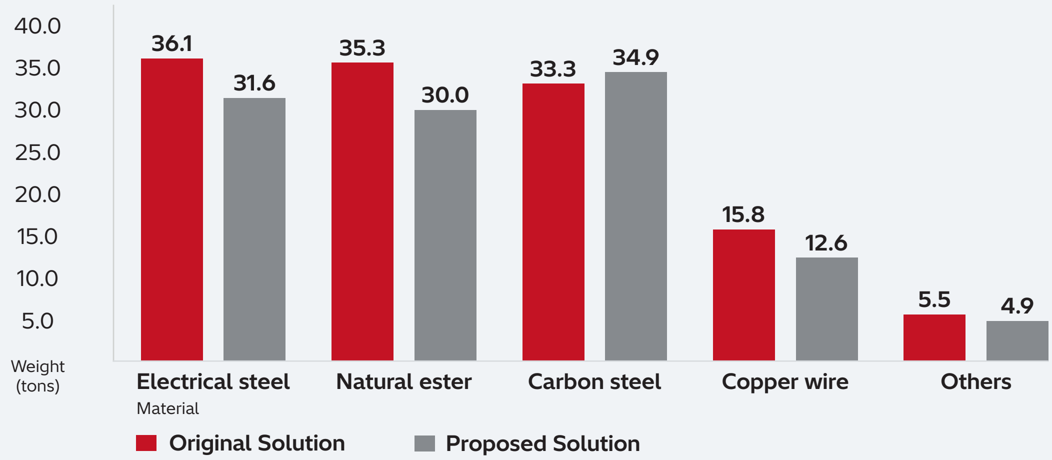
5.2.1.2 Carbon footprint implications

The proposed solution reduces material use and thus the GHG impact from material extraction and processing for transformers. As this life cycle stage determine around 90% of GHG Scope 3 emissions for end users from transformers procurement, the proposed solution is also a contribution to supporting data centers on their path to a net zero future.

Case #1 – 120MVA, 138/34.5 kV, Power Transformer

Material Weight [kg]
Total weight reduced by ca. 12 ton or 9%

Material weight analysis: Case #1



Global Warming Potential [kg CO_2 eq]
Total climate impact from materials reduced by ca. 37 ton CO_2 eq or 11%

Material CO_2 impact analysis: Case#1

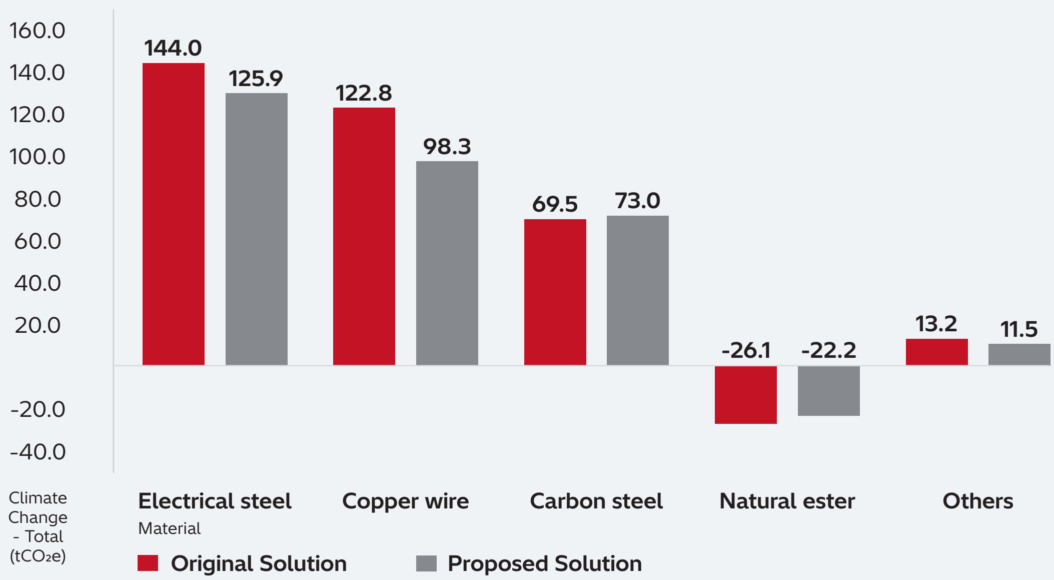


Figure 3 – Case #1, GHG carbon footprint reduction impact

5.2.2 Case #2 – 150MVA, 345/34.5 kV, mineral oil

The original customer requirements ask for design solution with delta connected high voltage (345 kV) with de-energized tap changer (DETC), on load regulation through On Load Tap Changer (reactor type OLTC) on LV side, operated at constant flux voltage variation (CFVV - 7.1.1).

Again, addition of internal preventive auto transformers (PA), plus, due to high rated power, a series-transformer (booster) is also required in this case to reduce OLTC maximum current as per rated products available on the market. Booster is also installed inside the main transformer tank.

The proposed solution, besides removing DETC and adding OLTC on HV side, is also changing the following main parameters, as per explicitly comparison request from our customer:

- Changing HV delta connection into Star with neutral connection.
- Adding extra stabilizing winding.

Main rating data differences are summarized in the following Table 2.

150 MVA, 345 /34.5 kV Power Transformer					
	Original Design – 2A		Proposed Solution – 2B		
Parameters	HV	LV	HV	LV	Stabilizing winding
Power, MVA	90/120/150 MVA		90/120/150 MVA		50MVA
Voltage, kV	345	34.5	345	34.5	13.8
Vector group	Dyn1		YNyn0+d (graded neutral for HV)		
Regulation type	CFVV – Constant Flux		CFVV – Constant Flux		
Tap changer	HV reg: Off Load	LV reg: On Load	HV reg: On Load	LV reg: None	TV reg: N/A
Tap range	±2 x 2.5% (±5%) 362.25 kV to 327.75 kV	±16 x 0.625% (±10%) 37.95 kV to 31.05 kV	±8 x 2.5% (±10%) 379.5 kV to 310.5 kV	N/A	N/A
Other Details	IEEE Standard, 60Hz, Mineral oil, same performances (NLL, LL, BIL, Impedance, Temperature rise)				

Table 2 - Case #2, Designs comparison table

Important note: stabilizing winding was added to this alternative solution only because of customer request but, as described in next chapter 7.1.2, this was not indispensable and without it the additional saving and footprint reduction would have been even higher.

Also, it is important to mention that even if the original solution would have asked for STAR connection at HV side, OLTC would have remained on LV side and the overall comparison results would not have changed much, since the major impact is connected to the on-load tap changer position.

5.2.2.1 Comparative results

Figure 4 shows the 3D view model for the original and proposed solution.

The original solution has additional accessories such as DETC, PA under OLTC, that require quite high internal space, higher tank and oil.

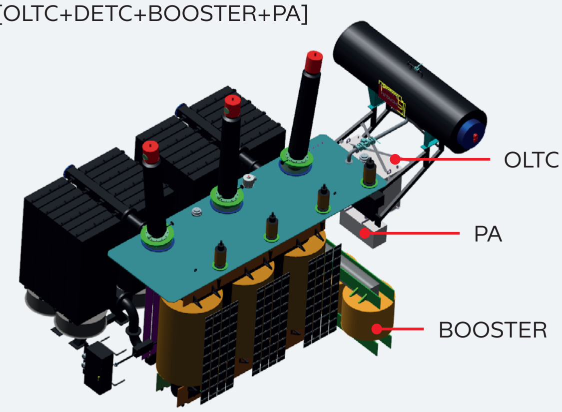
Moreover, in this case it requires a booster transformer also.

Similar considerations as per Case #1 can be made here overall, although this proposed alternative results even more impactful in terms of cost and footprint reduction.

Case #2: 150 MVA, 345/34.5 kV, Power Transformer

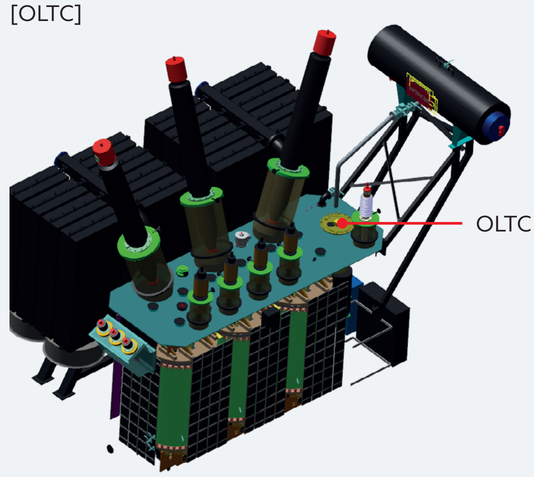
Original design-2A

[OLTC+DETC+BOOSTER+PA]



Proposed solution-2B

[OLTC]



Dimmension [mm]	Original design-2A	Proposed solution-2B	Benefit
Length	10,750	10,000	-7%
Width	7,350	6,600	-10%
Height	8,800	8,800	0%

Weight [kg]	Original design-2A	Proposed solution-2B	Benefit
Oil mass	64,000	43,500	-32%
Transport mass	139,000	101,000	-27%
Total mass	228,000	172,000	-25%

Figure 4 - Case #2, Comparative designs assembly and footprints

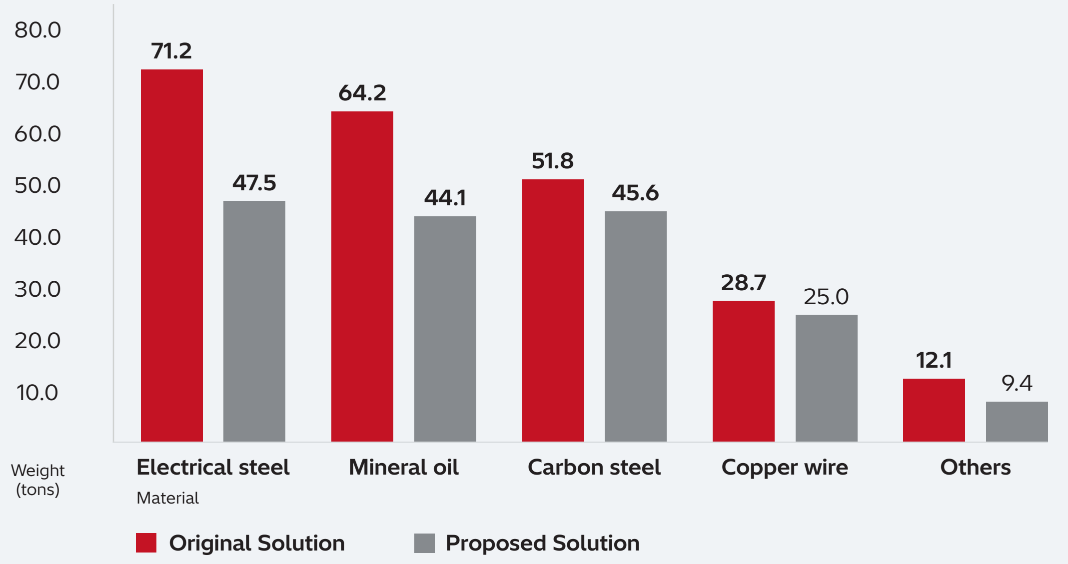
5.2.2.2 Carbon footprint implications

Similarly, as per Case #1, also with the proposed solution of case #2 we could reduce even further CO2eq by 24% as per summarized information in following Figure 5.

Case #2 – 150MVA, 345/34.5 kV, Power Transformer

Material Weight [kg]
Total weight reduced by ca. 56 ton or 25%

Material weight analysis: Case #2



Global Warming Potential [kg CO_2 eq]
Total climate impact from materials reduced by ca.177 ton CO_2 eq or 24%

Material CO_2 impact analysis: Case #2

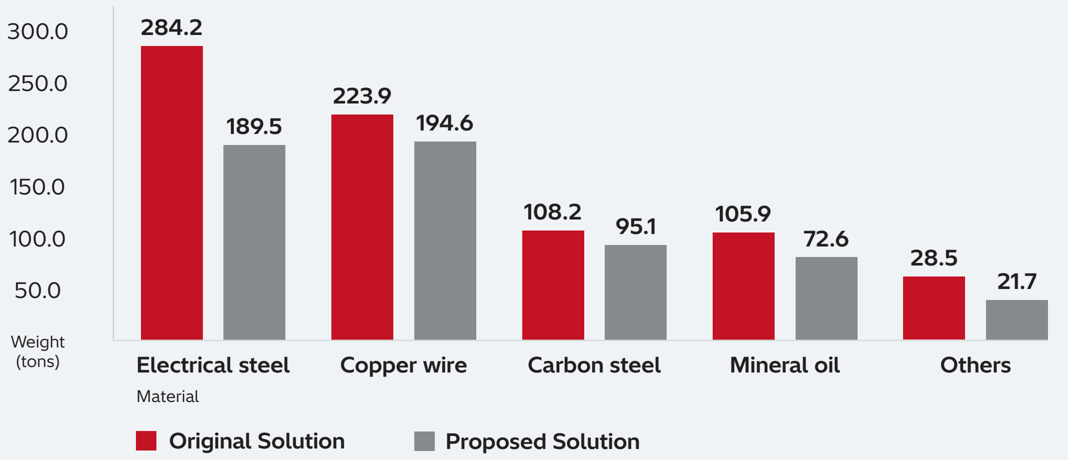


Figure 5 – Case #2, GHG carbon footprint reduction impact

5.2.3 Final comparison takeaways

Findings discussed in previous chapter 5.2.1 and 5.2.2 reveal that proposed solution offers a meaningful impact on optimized cost, footprints, dimensions and sustainability.

It is worth it to list advantages over a few disadvantages as per following summary:

PROS

- Reduced material cost, footprint and weight.
- Lower carbon footprint.
- Reduced no. of external elements in active part (DETC, PA & booster).
- Reduced maintenance and downtime having less external elements inside the tank.
- Better lead time removing dependencies from single source suppliers.
- Improved logistics & transportation reducing transformer size and shipping weight.
- Enabling dynamic allocation from multi-sources factory supply.
- Simpler asset management with digital monitoring.

CONS

- Delta connected HV for >220 kV needs three OLTC instead of one, will make solution complex but could be resolved moving to HV Star connection as per practice followed in other grids.
- LV rated voltage shall be specified at no load condition as per practice followed in other grids.

5.3 Trafostar™: Design anywhere, build anywhere

In a world where data never sleeps, the infrastructure behind it must be just as relentless. As data centers scale at unprecedented speed, they demand power solutions that are fast to deploy, globally consistent, and built for long-term reliability.

TrafoStar™, Hitachi Energy's globally unified transformer design and manufacturing system, rises to meet this challenge. With over 120 years of transformer innovation and 30 years of proven performance, TrafoStar™ has become a cornerstone of mission-critical power infrastructure. Its short-circuit test pass rate is three times higher than the industry average (CIGRE N.323, 2022), setting a new benchmark for quality and resilience.

Factors influencing the TrafoStar™ global technology

A standard and global design and manufacturing platform covering customer and market requirements

New technologies and regulations to build a safe, quality and reliable product

Why TrafoStar™ aligns with Data Center Demands:

- Scalable Capacity: With a projected installed base exceeding 500 GVA by 2030 and a global network of 17 manufacturing facilities, TrafoStar™ ensures rapid, scalable deployment to support data center growth anywhere in the world.

- Standardization with Flexibility: Built on a global Technology Platform, TrafoStar™ combines standardized components and modules with the flexibility to deliver tailor-made designs—meeting specific site, performance, and regulatory requirements.

- Speed and Consistency: Advanced design and simulation tools streamline engineering cycles, enabling faster delivery while maintaining consistent quality across global deployments.

- Digitalization and Sustainability: Through full automation and digitalization of processes, and 100% fuel-free operations since 2022, TrafoStar™ supports the sustainability and efficiency goals of modern hyperscalers.

- Proven Legacy, Future-Ready: Every Power Transformer delivered today is built on the TrafoStar™ foundation—representing a combined technology heritage of over 250 years with Hitachi Japan and a relentless commitment to innovation.

Whether supporting hyperscale campuses or distributed edge facilities, TrafoStar™ transformers deliver the performance, reliability, and global consistency that data centers infrastructure demands.

6 Conclusions

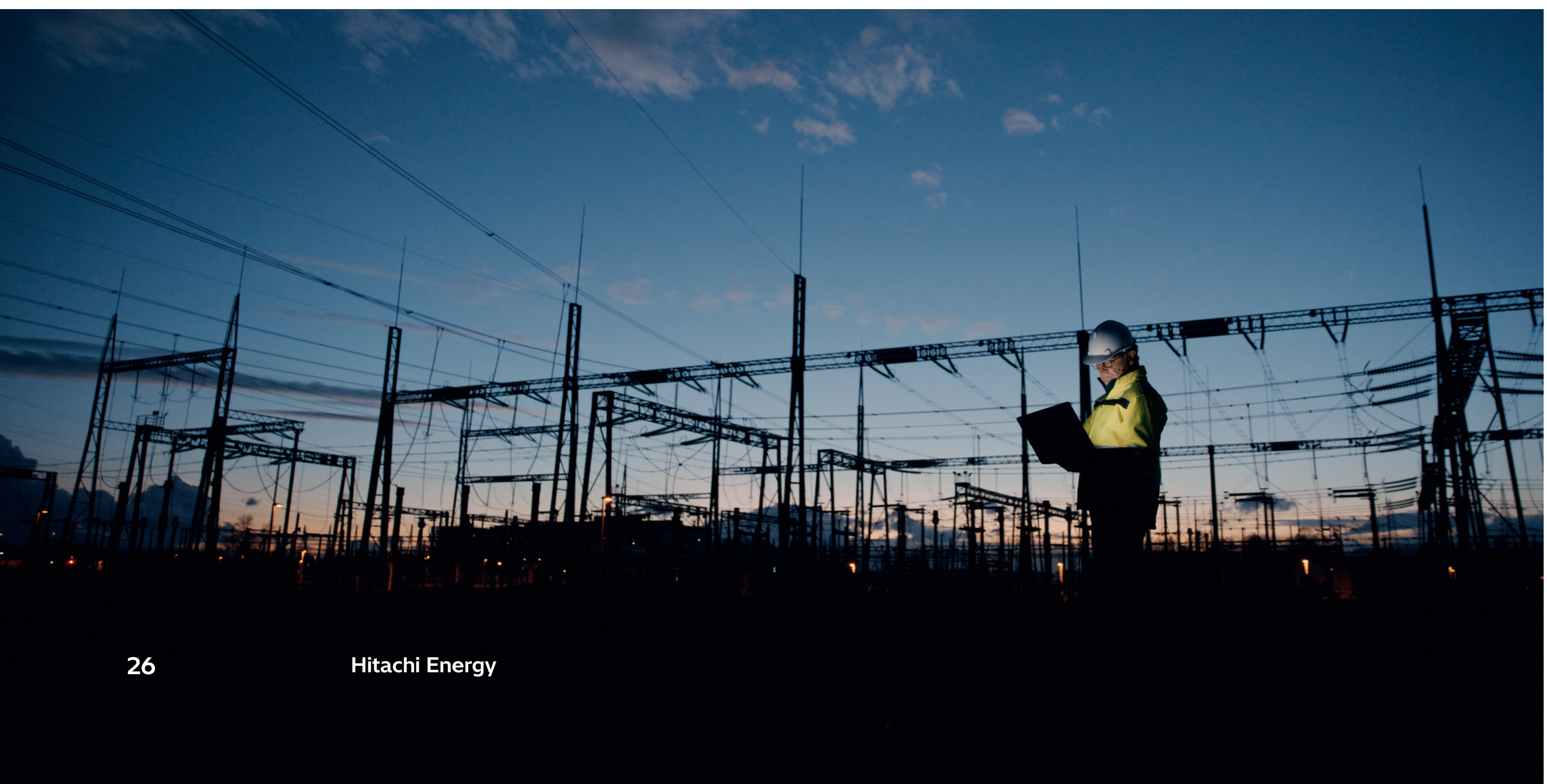
The accelerating growth of global data centers—driven by AI, cloud computing, and digital transformation—is placing unprecedented demands on power infrastructure. As utilities and data center operators face mounting challenges from long transformer lead times, supply chain constraints, and evolving grid requirements, it is clear that traditional approaches are no longer sufficient.

This article underscores the urgent need for a paradigm shift in transformer design, procurement, and deployment. By embracing standardized yet flexible solutions like Hitachi Energy's TrafoStar™, stakeholders can unlock scalable, globally harmonized manufacturing capacity while reducing complexity, cost, and environmental impact.

The comparative analysis of transformer configurations reveals that moving OLTCs to the HV side still adopting constant flux voltage variation (CFVV) regulation simplifying component architecture, can significantly reduce lead times, material usage, and carbon footprint—without compromising performance. These innovations not only enhance operational agility but also align with the sustainability goals of modern hyperscalers.

Moreover, regional insights into grid transmission practices and philosophies highlight the importance of tailoring transformer specifications to local conditions while leveraging global best practices. The proposed solutions demonstrate how utilities and data center operators can co-create resilient, future-ready infrastructure that meets the dual imperatives of speed and sustainability.

In conclusion, the path forward lies in **collaborative innovation, early engagement with OEMs, and strategic standardization.** By rethinking transformer design and deployment strategies, the industry can overcome today's constraints and power the next generation of digital infrastructure.



7 Additional Information

7.1 Constant Flux and Variable Flux transformer regulations

Both types of regulations are well described in industry standards IEEE and IEC. The most adopted regulation worldwide in mainstream substation and GSU transformers is the CFVV, constant Flux voltage variation regulation, since it is normally cheaper and more compact in terms of Transformer design solutions at similar required performance ratings. This happens to be regardless of whether it is LV or HV on-load regulation methodology.

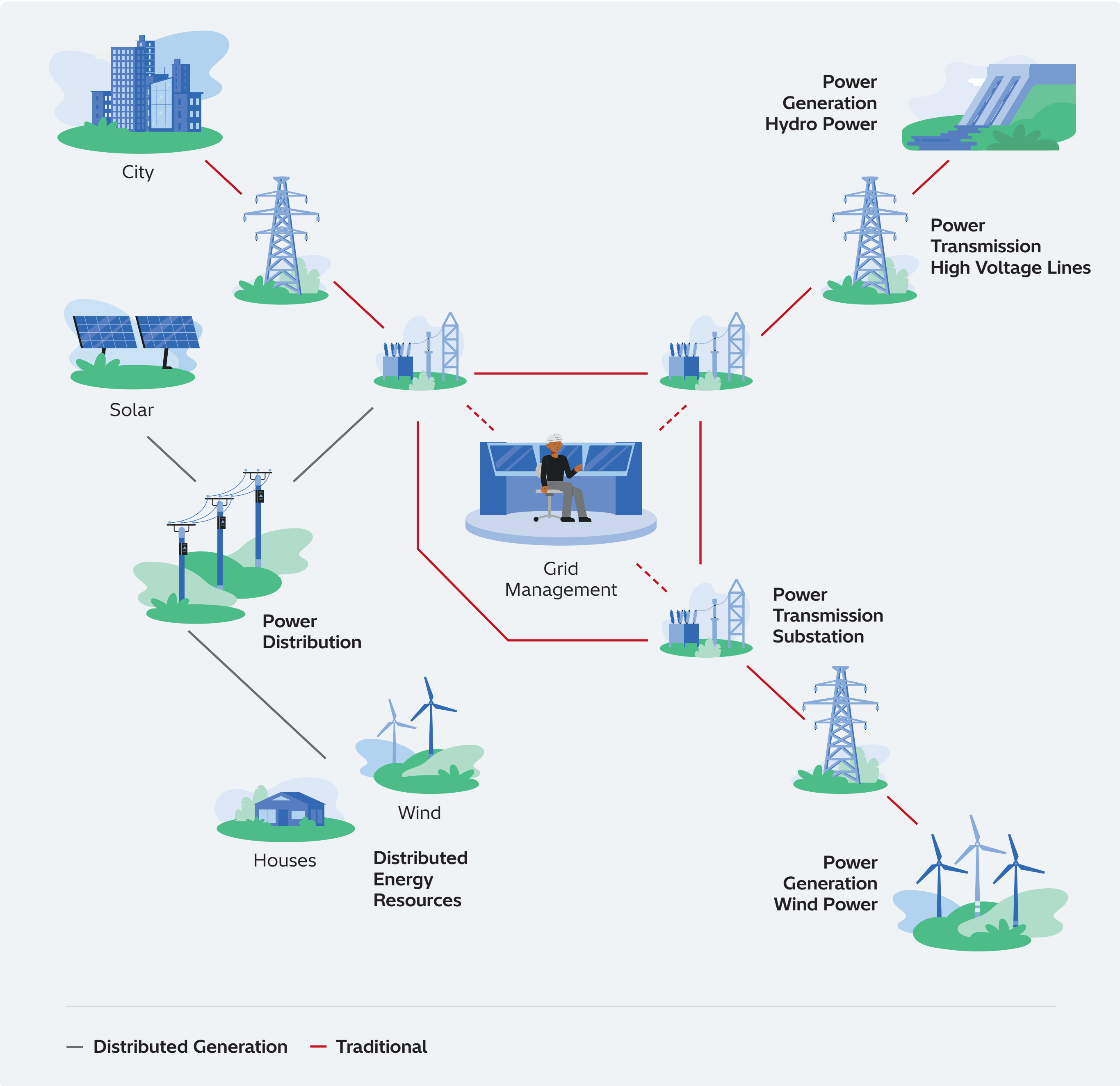
7.1.1 CFVV – Constant Flux and Variable Voltage

Constant Flux Voltage Variation (CFVV), This is a voltage regulation principle used in transformers where the magnetic flux in the core remains constant. The voltage in any non-regulated winding remains constant at any tap in regulated winding. The regulating voltages in the regulated winding are proportional to the tapping factors. This is typically achieved using an On-Load Tap Changer (OLTC), which adjusts the number of turns in winding according to required voltage. The key idea is to maintain a constant flux in the core keeping voltage per turn uniform across the winding. This approach offers several operational benefits, such as stable no-load losses, sound levels, uniform step voltages and minimal impedance variation.

Typical north America market requires DETC on HV side and Reactive type OLTC on LV side, looking back for this traditional approach being followed today probably depicts that HV side voltage is preferably remaining constant in grid since DETC can't be operated unless units switched off from the grid and there is a fluctuating load (e.g. resistive, inductive or capacitive) to the network that really needs to be controlled by reactive tap changer on LV side that may along needs it's counter parts as booster and preventive auto transformer.

While comparing the same practices in other parts of globe (e.g. Europe, Asia, China, Middle East, Africa etc.), all utilities and data center operators prefer to have OLTC on the high-voltage (HV) side to absorb grid voltage variation keeping LV constant with CFVV type regulation.

In today's scenario, grids are growing very rapidly with huge addition of power generated from renewable sources (like wind & solar, on-shore & off-shore), this will make grid operation quite complex and challenging to maintain stability and voltage variation. Needless to mention that voltage generation by different methods (thermal, hydro and nuclear) may also bring voltage variation to the grid.



Traditional vs Distributed Generation Grids

To address this voltage variation either in grid (supply side) or load side, normally automatic voltage regulator is installed facilitating automatic trigger to OLTC correcting required voltage online from time to time. Nowadays, with recent technological advancements, all customers are using automatic voltage regulators facilitating automatic control of voltage by sensing voltage and current signals, triggering required command to tap changer. Further, it's also possible to detect reverse power flow conditions as well.

7.1.2 Wye-wye connected transformer plus delta winding[12]

Wye-wye connected transformers are commonly applied in several voltage transformation stages in today's power system due to the advantage of simple phasing of terminals, availability of a secondary neutral point for grounding and the (vectorial) split of the line-to-line voltage over two series-connected phase windings.

However, wye-wye connected transformers faces potential issues as neutral point voltage instability due to unbalanced load, higher zero sequence impedance, interference to telephonic lines and induction of third harmonic voltage.

Due to above, wye-wye-connected transformers, a third, delta-connected winding may be required for the main purpose of stabilizing the phase-to-neutral voltages under unstable, reducing third harmonics of exciting current and zero-sequence current. This delta connected winding can be termed as stabilizing (not brought out) or tertiary (for connection to external load).

In three-legged core designs without a delta winding, the path for return of the zero-sequence flux is through the space between the transformer's core and the tank called as virtual delta winding, reduces the zero-sequence impedance at a lower cost. Three-phase, three-legged core transformers become less susceptible to line-to-neutral voltage distortion because of the high reluctance path for the zero-sequence flux. Additionally, modern power transformers with high-grade silicon steels exhibit very low exciting currents, from which harmonics are a small fraction (negligible). Further, it is also noted that modern telephone technology is vastly superior that telephone interference problem is not as serious as it was in the past.

A design with a stabilizing winding would be on the safe side of all possible considerations regarding those phenomena, at a potentially unnecessary extra cost. On the other hand, the benefits of eliminating the stabilizing winding can include not only the economics but also may reduce the number of components exposed to short-circuit currents, which is normally considered as weak link in the transformer.

In some applications, there would be no trouble if the stabilizing windings were omitted from transformers due to loads on transmission lines being balanced, upgradation in telephonic technology and moder relaying equipment.

With improved technology and changed conditions, the idea that a stabilizing winding is not needed in all cases has been recognized by some electric utility companies who have purchased, and had in operation for many years, wye-wye-connected transformers and wye-connected autotransformers without stabilizing windings

- 10-160 MVA, 11-138 kV, 3 phase, wye-wye connected unit without delta winding in US during 1950's[13].
- 900 to 1600 MVA (three phase bank), 525/241 kV, auto-transformer, AEP, 7 banks are installed without delta winding in US[14].

7.2 Listing of related documents

Ref #	Document kind, title	Document No
[1]	*U.S. Electric Power Transmission Lines - Visualization*	
[2]	*Brazil's Transmission Outlook: Strategic plan for expanding grid over next decade - REGlobal - Mega Trends & Analysis*	
[3]	*Map of Columbian Electricity Grid - Columbia - National Energy Grids - Library - GENI - Global Energy Network Institute*	
[4]	*Mexico GPT2025 | Pan American Finance*	
[5]	*ENTSOE - ENTSOE_Grid_Map*	
[6]	Standard Specification and technical parameters for transformers and reactors (66 kV & Above), Issued by Government of India, Ministry of Power, Central Electricity Authority	CEA-PS-14-169/2/2019
[7]	*ESCAP - 2019-FS-Electricity-connectivity-roadmap-Asia-Pacific*	
[8]	CIGRE ELECTRA August 2022 by René Smeets and Bas Verhoven	N.323
[9]	Data Center Carbon Footprint: Scope 1, 2, & 3 Emissions	
[10]	The first comprehensive attempt to quantify data center Scope 3	
[11]	Climate - Meta Sustainability	
[12]	IEEE guide for application of tertiary and stabilizing windings in power transformer	IEEE C57.158
[13]	B.A. Cogbill, "Are stabilizing windings necessary in all Y-connected Transformers"	AIEE Transactions, pp. 963–970, October 1959.
[14]	P.L.Bellaschi, "Tertiaries in large Power Transformer Banks – The problems they present (a Case Study)"	Doble International Conference papers – Paper 6-701
[15]	McKinsey & Company	Data center demands
[16]	International Energy Agency	Energy Demand from AI and Electricity Analysis 2025
[17]	GlobalData	Data Centers – Impact on the Power Sector

7.3 List of acronyms

Abbreviation	Description
CFVV	Constant Flux Variable Voltage
VFVV	Variable Flux Variable Voltage
HV	High Voltage
LV	Low Voltage
TV	Tertiary Winding
NLL	No Load Losses
LL	Load Losses
OLTC	On Load Tap Changer
DETC	Deenergized Tap Changer
PA	Preventive Auto transformer
SA	Series Auto transformer
AVR	Automatic Voltage Regulator
NER	Neutral Earthing Resistor
NGR	Neutral Grounding Resistor
CEA	Central Electricity Authority
SW	Stabilizing Winding
TW	Tertiary Winding
BIL	Basic Insulation Level
GHG	Greenhouse gas

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