GE VERNOVA

POWER TRANSFORMERS FOR THE GRID OF THE FUTURE

The World's First Flexible Power Transformer

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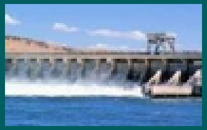
About GE Vernova

A built-for-purpose energy transition company

POWER

Gas Power
- Heavy Duty Gas Turbines
- Aeroderivative Gas Turbines
- Steam Turbines/Generators

Steam Power
- US Nuclear, Global Coal
- Steam, Generators, Boilers



Hydro
- Hydro Turbines/Generators
- Pumped Storage

Nuclear
- Boiling Water Reactors
- Fuel
- Small Modular Reactors

WIND

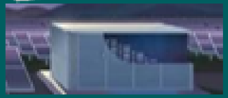
Onshore Wind
- 2 - 3.5 MW platform
- 5 – 6 MW platform
- Services & repowering

Offshore Wind
- Haliade-150 (6 MW)
- Haliade-X (14 MW)

Wind Power
- ONW blades
- Haliade X blades

ELECTRIFICATION

Grid Solutions
- Transmission
- Transformers
- Grid Automation



Power Conversion & Storage
- O&G, Rails & Ports, Electrification
- Marine, Navy & Heavy Industry
- Battery Energy Storage
- Solar inverters

Electrification Software
- GridOS
- Manufacturing
- Power and O&G

ACCELERATORS

Financial Services
- 3rd Party financing support
- Direct financing though equity

Consulting Services
- Power Market Assessments
- Investment Decision Analysis

Advanced Research
- Differentiated Technologies
- External Partnerships

GE Vernova in numbers

~7,000
gas turbines installed - the world's largest fleet

2,324 GW
global installed base across our Power and Wind segments

3+ GWh
battery energy systems operational globally

1ST
commercial contract for a small modular reactor in North. America

30 GW
solar inverters global installed base

$4 BN+
orders for GE Vernova technologies enabled by Financial Services in 2023

~55,000
wind turbines installed in 50+ countries

#1 U.S.
onshore wind turbines provider for the 5th year in a row*

117+ GW
global wind installed generating capacity

90%
of global power transmission utilities have been equipped with GE Vernova technologies

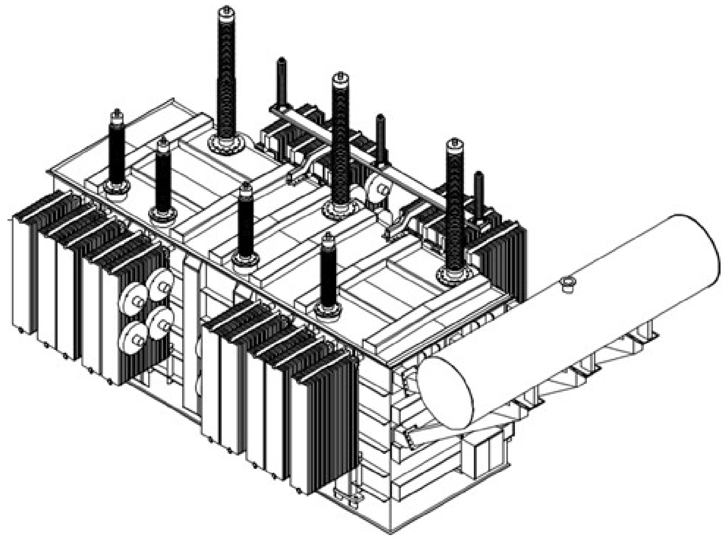
~$1 BN
invested in annual R&D across Advanced Research + our businesses, ~3% of 2023 revenue

30%
of the world's utilities are served by our software

~25% of the World's electricity is generated with GE Vernova's technology

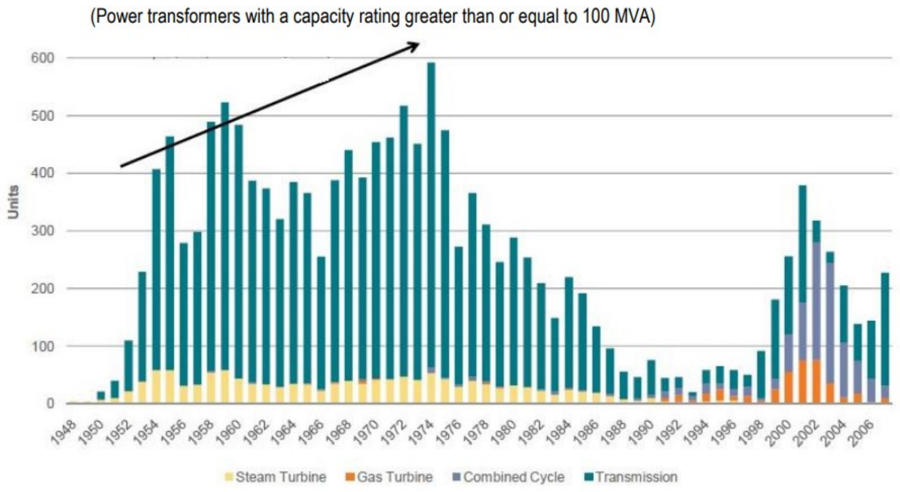
About power transformers

And why rethinking their design matters in today's context



- Large Power Transformers (LPTs):
  - Per our definition, with power capacity greater than 100MVA
  - Custom-made (**production per design ratio ~1.3** - Source: DOE);
  - Long-lead times, difficult to transport, and expensive which lead to high spare inventory costs
  - Weather extremes, load and generation volatility to require more support for optimal power flow dispatch (Grid enhanced technologies – GETs)

- About the US fleet
  - average age of U.S. populations of LPTs ~38 years, 70% being +25 years old (Source: DOE).



  - Surging demand for electrification & decarbonization (Datacenters, EV, Renewables)
  - US import +80% of its LPT demand (Source: DOE)

In this context, will more flexible LPT better support the grid and improve its reliability and resilience?

Source:

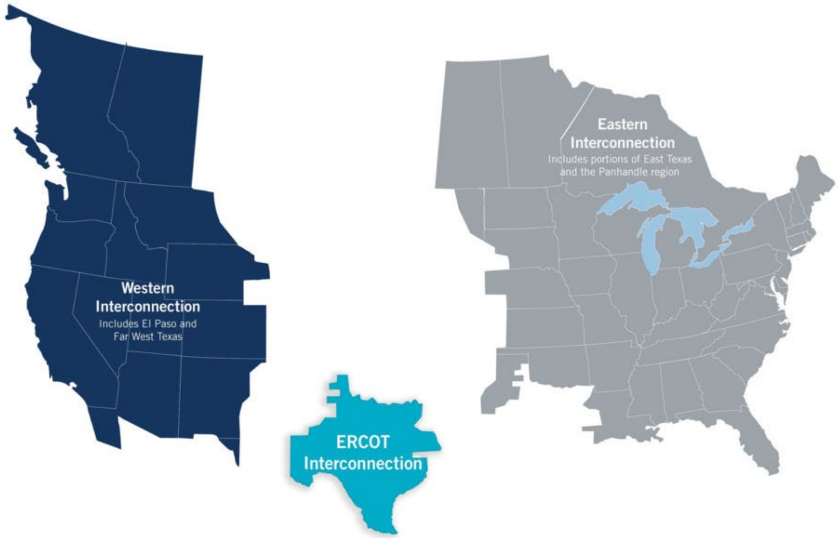
- DOE, Large Power Transformers and the U.S. Electric Grid, April 2014
- DOE, Large Power Transformer Resilience, July 2024

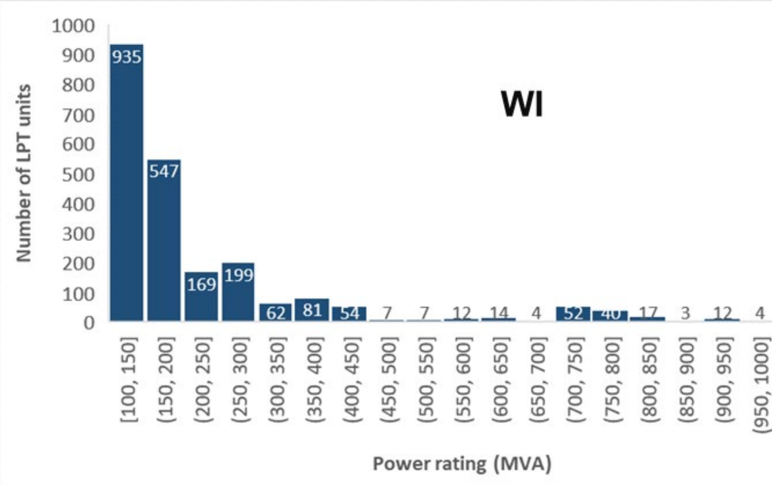
A deeper look into the US fleet

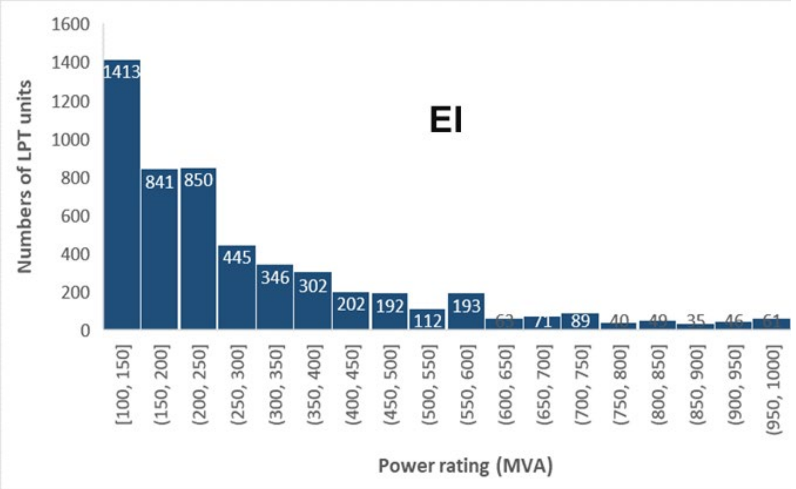
WECC interconnection (WI)
- 9,126 transformers
- 2,221 LPTs

Eastern interconnection (EI)
- 14,898 transformers
- 7,502 LPTs

Source: Transformers data obtained from GE Vernova Energy Consulting database







- LPTs represent ~40% of the total power transformers installed in the US
- 100MVA to 150MVA is the largest segment and account for 18.8% in EI and 42.1% in WI

A deeper look into the US fleet

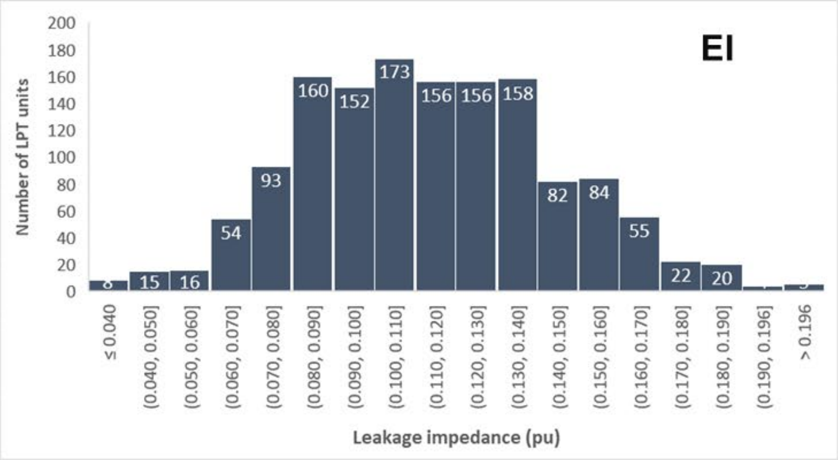
The voltage and impedance characteristics of 100MVA to 150MVA LPTs

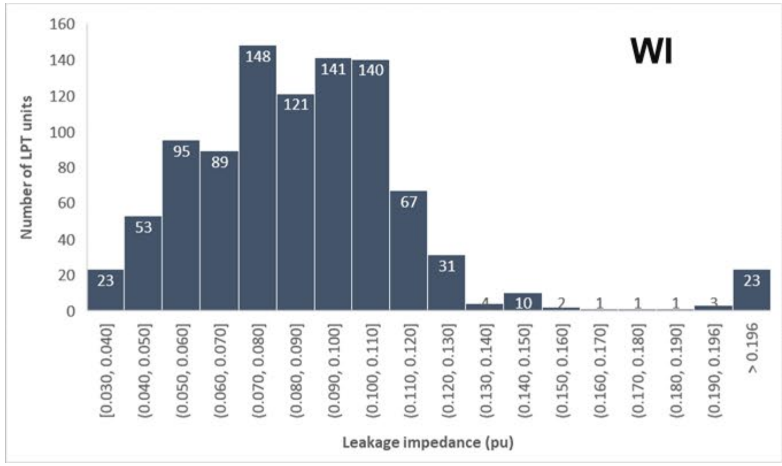
EI

High Voltage side (kV)	Low Voltage side (kV) 345	230	161	138	115	69	<35	Total	Trans. class LPTs only
500	0	0	0	0	1	1	19	21	1
345		0	0	2	2	0	19	23	4
230			4	12	53	66	255	390	69
161				5	18	124	48	195	23
138					115	157	199	471	115
115						31	211	242	0
	0	0	4	19	189	379	751	1342	212

WI

High Voltage side (kV)	Low Voltage side (kV) 345	230	161	138	115	69	<35	Total	Trans. class LPTs only
500	0	0	0	0	2	3	28	33	2
345		8	0	3	18	1	11	41	29
230			13	81	88	182	314	678	182
161				1	2	0	0	3	3
138					1	13	37	51	1
115						11	26	37	0
	0	8	13	85	111	210	416	843	217





- 19.6% of 100MVA to 150MVA LPTs are transmission class transformers
- 230kV is the most common HV side voltage used by the 100 to 150MVA transmission class LPTs
- 161kV, 138kV, and 115kV are the most common LV side voltages For used by 230kV HV side
- +80% of the 100MVA to 150MVA LPTs have a short-circuit impedance between 4% and 14%

A flexible LPT should be customizable for different Voltage, Impedance and Power ratings

What a flexible power transformer should be?

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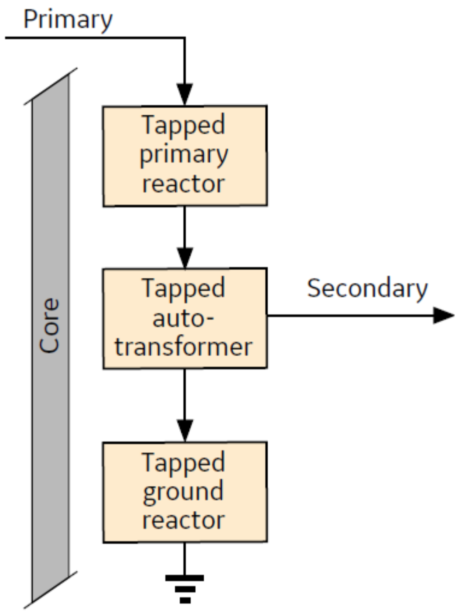
- Autotransformer or conventional transformer
- **Adjustable leakage impedance (online or offline)**
- Connectable at different voltage class

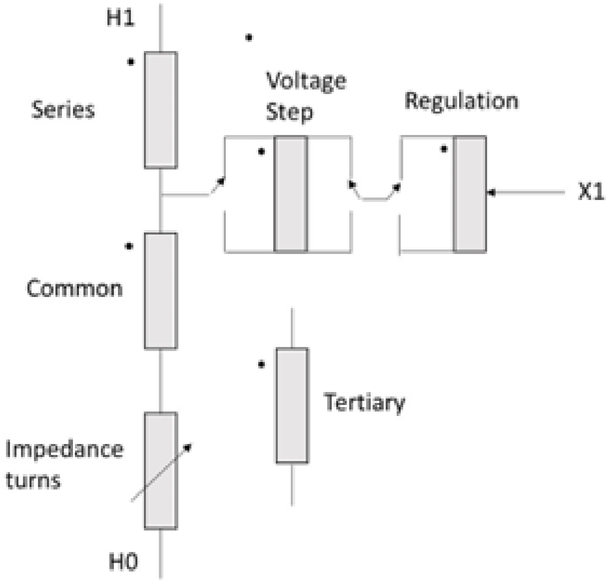
Specific design challenges for flexible power transformers

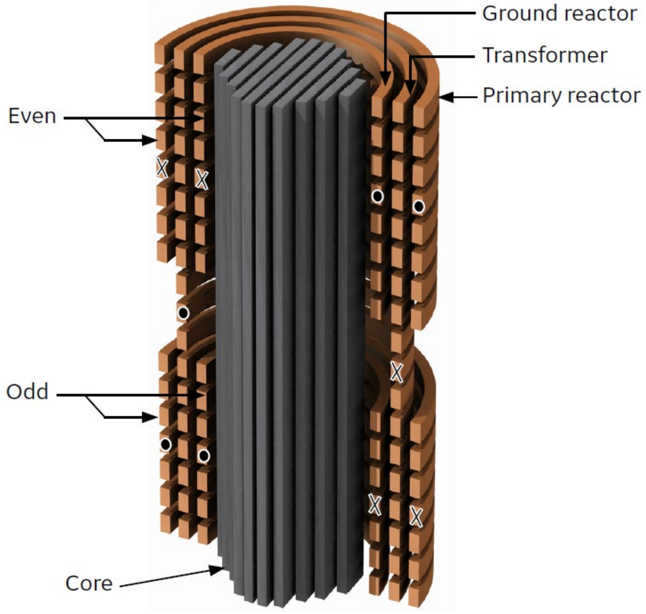
- Can the flexible LPT design meet standards requirements (e.g. IEEE C57)?
- Can the flexible LPT footprint be within 120% of similarly sized regular LPTs?
- Can the flexible LPT impedance be adjusted online without adverse impact?
- Can the protection settings be updated online following an impedance change?

Flexible power transformer concept

An innovative concept: autotransformer with flexible low voltage and adjustable leakage impedance for transmission application







Potential Applications of Flexible Power Transformers

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Universal spare coverage

- Single or multiple voltage rating
- Off-line adjustable impedance

Applications

- Coverage for targeted substations or a specified fleet
- Short-circuit management for evolving grid

Power Flow Controller

- Single-voltage rating
- **<u>Online</u>** adjustable impedance

Applications

- Power flow control & congestion management
- Contingency management & grid stability
- Emergency response

User case 1: Application as a Universal Spare for the US fleet

100MVA-150MVA flexible LPT

Item	Description
Application	Autotransformer (transmission)
HV Voltage Class	230 kV
LV Voltage Class	115 kV/ 138kV / 161kV
Rated capacity (ONAN)	100 / 120 / 150 MVA
Maximum capacity (ONAF)	166 / 200 / 250 MVA
Impedance Range	4% to 14 % @ 100 MVA

Can replace **26 units** in the EI and **75 units** in the WI corresponding respectively to 37.7% and 41.2% of 230kV, 100 to 150MVA transmission class LPTs

250MVA-300MVA flexible LPT

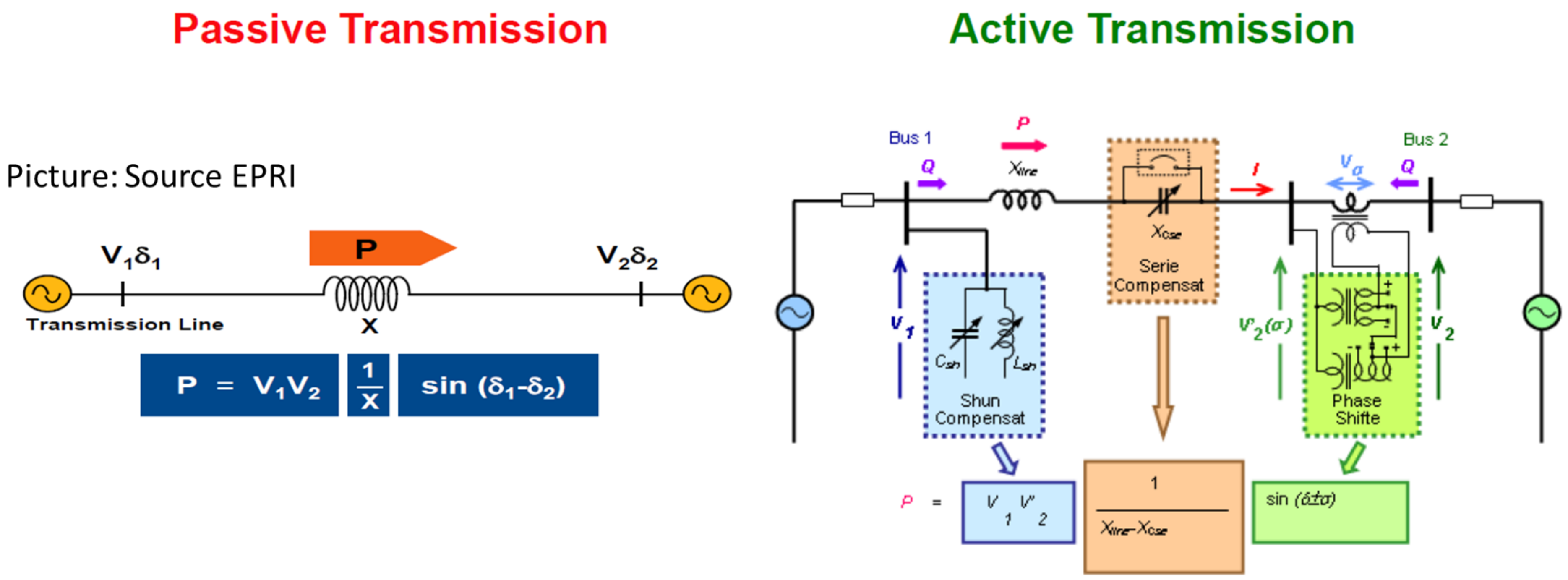
Item	Description
Application	Autotransformer (transmission)
HV Voltage Class	345 kV
LV Voltage Class	115 kV / 138kV / 161kV
Rated capacity (ONAN)	230 / 260 / 290 MVA
Maximum capacity (ONAF)	383 / 433 / 483 MVA
Impedance Range	4% to 14 % @ 200 MVA

Can replace **23 units** in the EI and **11 units** in the WI corresponding respectively to 92% and 42.3% of 345kV, 250 to 300MVA transmission class LPTs

- A much smaller spare coverage level would be required by utilities
  - A universal spare can be cost-effective if it can replace 2 spare units
  - Ideal scenario is 1 universal spare to replace +3 spare units

User Case 2: Flexible Power Transformer as a Power Flow Controller

- Power flow control (PFC) is one of GETs
- The flexible transformer combines in one **single equipment** the function of a conventional transmission class transformer and that of a series compensation system which allows it to be cost-effective for most transmission lines seeking PFC.



A flexible power transformer can be the most cost-effective way for power flow control

Prototyped flexible power transformer for field validation

Prototype specifications

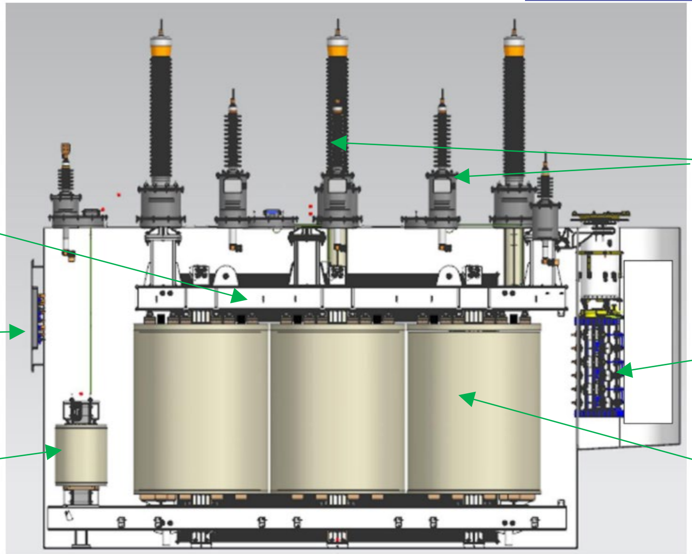
Autotransformer
60/80/100 MVA
(12/16/20 MVA External Tertiary)

			Connection	BIL
VH	161 kV		Y	650
VX	57.5/**69**/80.5 kV		auto	350/150
VY	13.8 kV		D	110
3Ph	ONAN/ONAF/ONAF	60 Hz	65 °C	

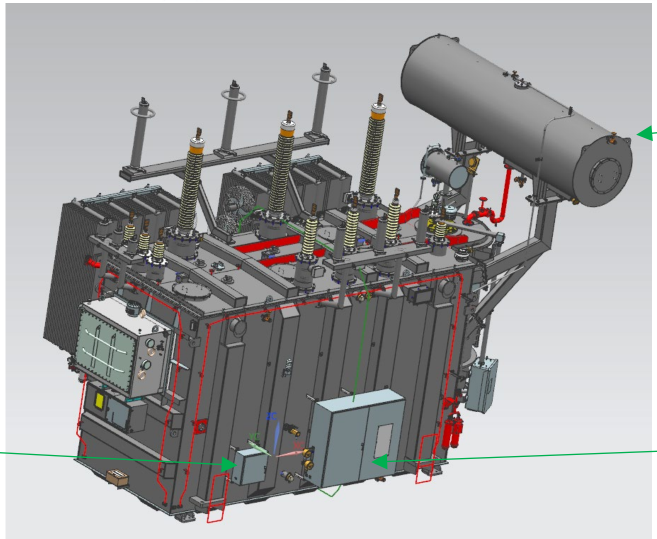
On-line Impedance Variation range
ZH-X = 4.2 to 9.3% @ 60 MVA

Voltage regulation (in LV line)

Internal layout



External layout



Same material and engineering procedures as applied to today's conventional transformers

World's 1st Flexible Power Transformer

With 3 configurable LV ratings and an online adjustable leakage impedance

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Autotransformer
60/80/100 MVA
(12/16/20 MVA External Tertiary)

			Connection
VH	161 kV		Y
VX	57.5/**69**/80.5 kV		auto
VY	13.8 kV		D
3Ph	ONAN/ONAF/ONAF	60 Hz	65 °C

On-line Impedance Variation range
ZH-X = 4.2 to 9.3% @ 60 MVA

Voltage regulation (in LV line)
+/- 10% of rated voltage in 16 taps

Designed and tested according to

- IEEE C57.12.00 IEEE Std for General Requirements of Liquid-Immersed Transformers
- IEEE C57.12.90 IEEE Std Test Code for General Requirements of Liquid-Immersed Transformers

Flexible power transformer prototype as installed in the field and ready for operation

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- Energized on 10/3/2021 at **Cooperative Energy's** Columbia substation in Mississippi USA

Flexible protection system for flexible transformer

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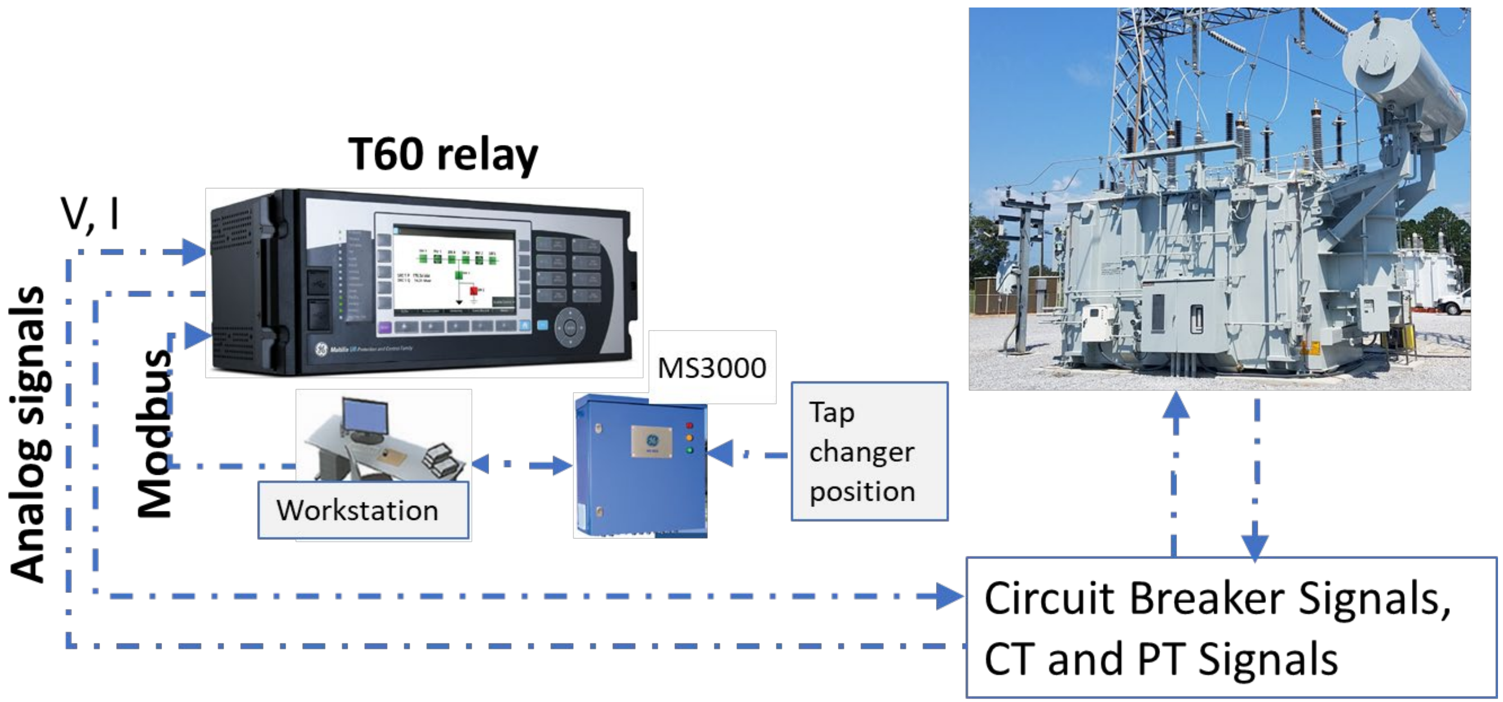
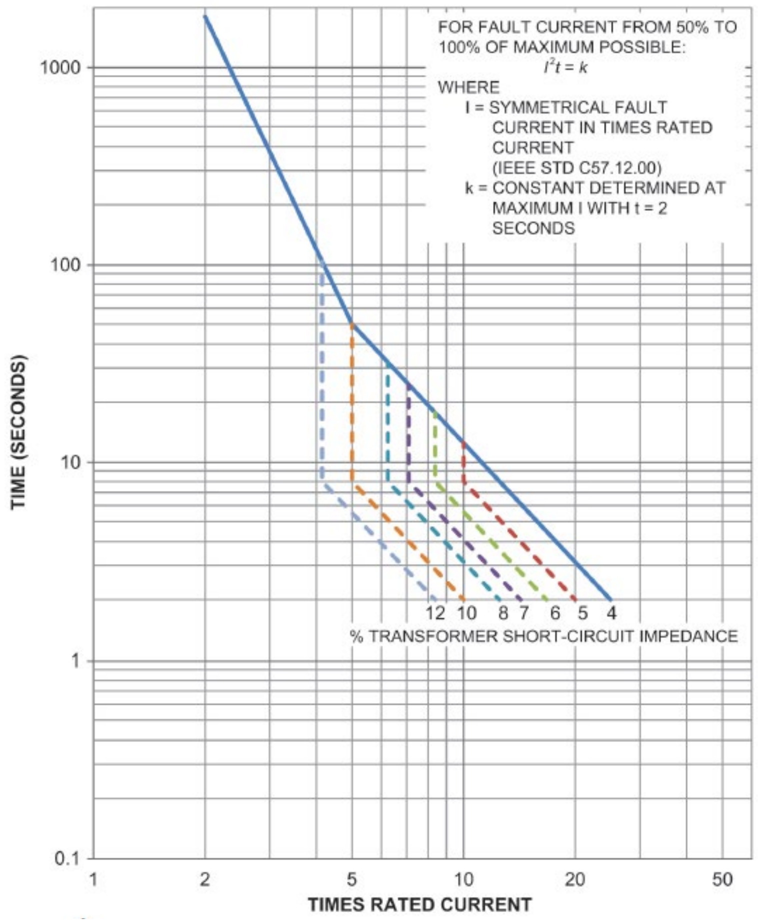


Tested values of online adjustable Impedance range

IMPEDANCE @ 85°C

IMPEDANCE TAP CHANGER DIAL POSITION	kV BASE 165.025 / 80.5 / 13.8, kVA BASE 69 000			165.025 / 69 / 13.8, kVA BASE 60 000			165.025 / 57.5 / 13.8, kVA BASE 54 000		
	%Z H-X	%Z H-Y	%Z X-Y	%Z H-X	%Z H-Y	%Z X-Y	%Z H-X	%Z H-Y	%Z X-Y
8R				9.34	4.495	3.060			
7R				8.714	4.611	3.125			
6R				8.125	4.734	3.216			
5R				7.568	4.861	3.324			
4R				7.045	4.992	3.45			
3R				6.549	5.124	3.597			
2R				6.090	5.254	3.762			
1R				5.666	5.395	3.943			
NOM				5.267	5.535	4.144			
1L				4.918	5.679	4.37			
2L				4.599	5.829	4.617			
3L				4.309	5.981	4.885			



IEEE Std C57.109-2018 IEEE Guide for Liquid Immersed Through Fault Current Duration

Flexible power transformer validation in the field

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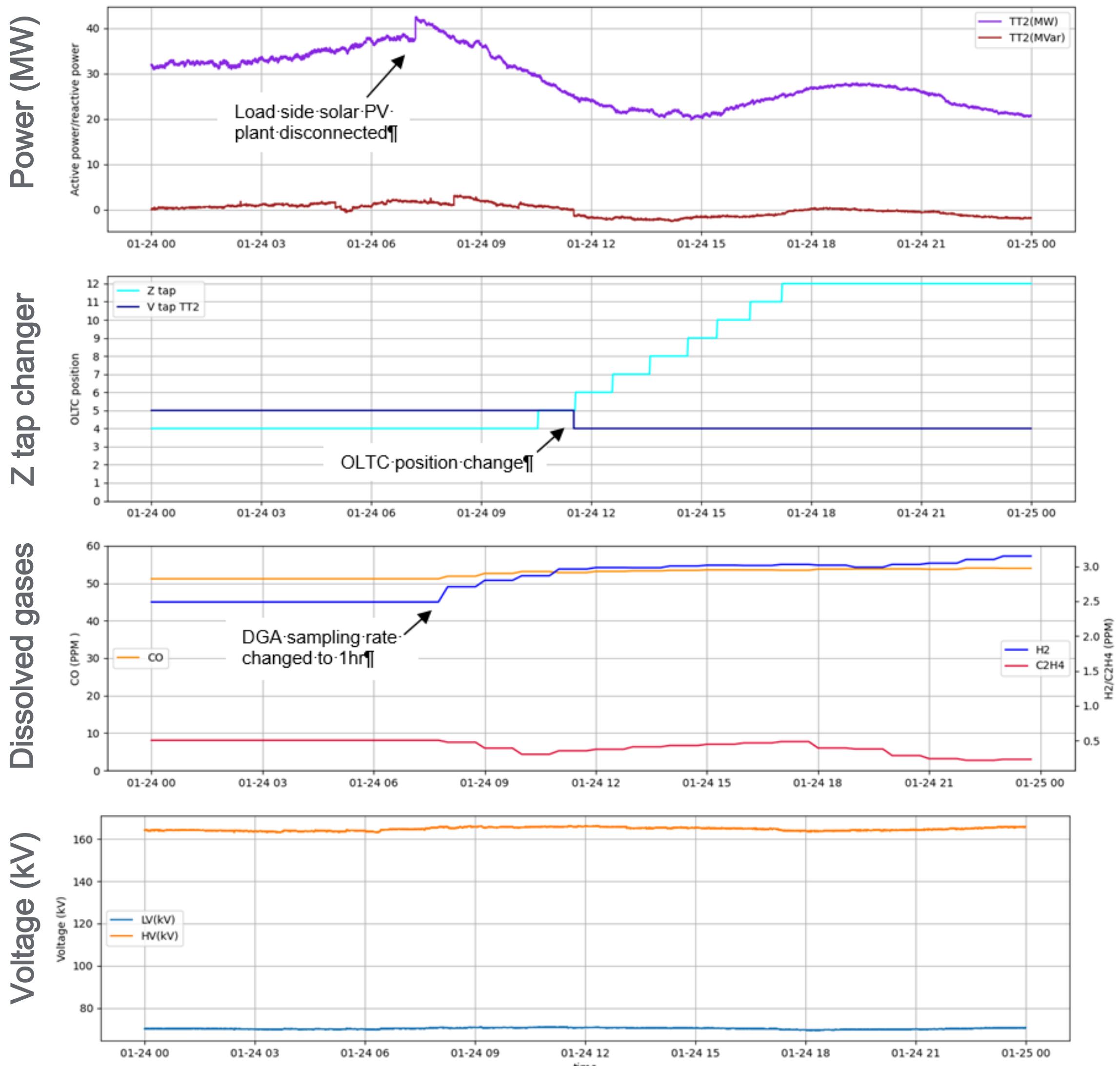
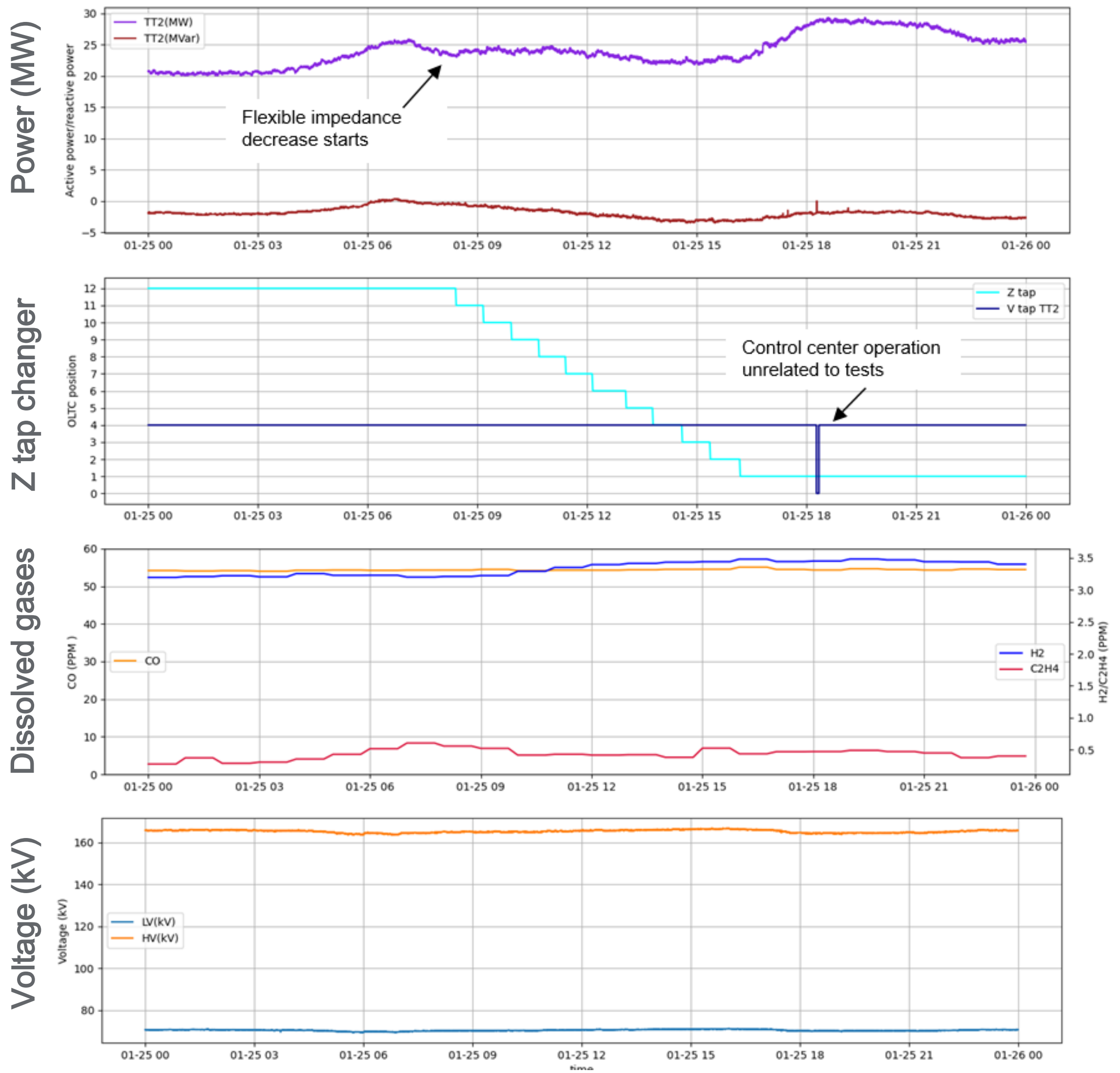
Power flow control





Power flow control with no adverse impact on the grid

Emerging Power Transformer Technologies:
Solid State Transformer (SST)

Solid State Transformer

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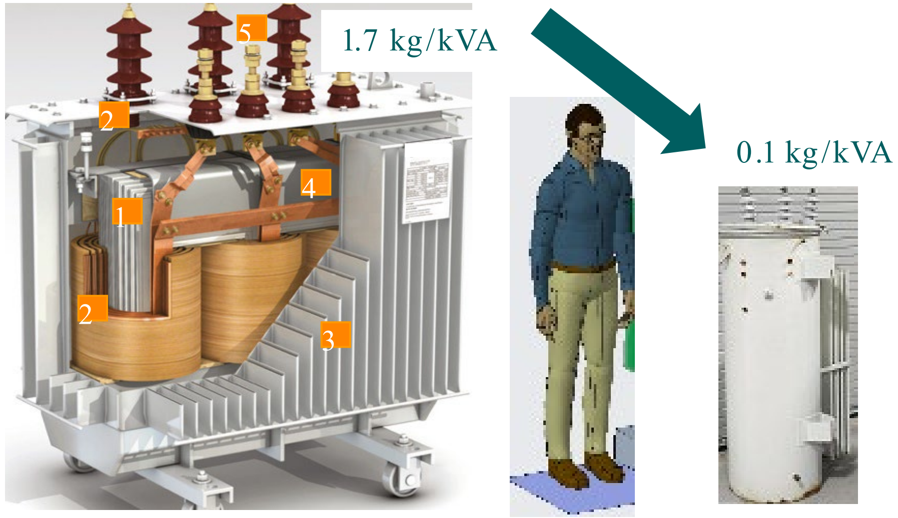
Economic trend

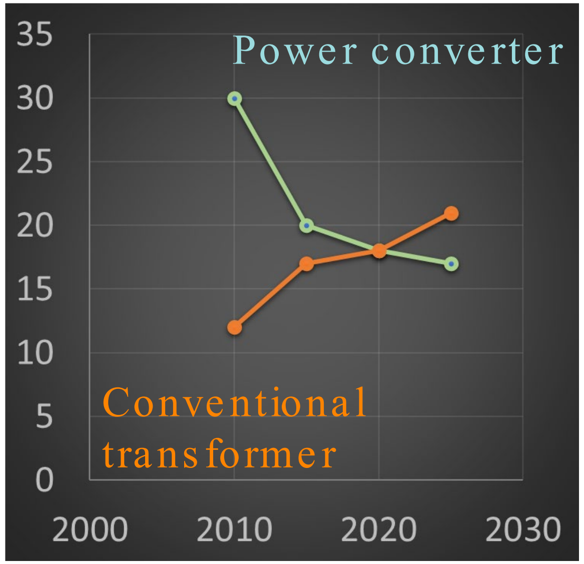
- During last 15 years cost of power converters reduced from ~30$/kVA down to ~17$/kVA
- In 2020 line -frequency inverter was no more expensive than utility grade transformer

SST power scale -up 250kVA ↗ Multi MVA tradeoffs

- Power density↑ Vs losses/cooling↑
- Magnetics GOES @ medium frequency vs Nano-crystalline @ high frequency
- Converter losses
- Modularity @ MV voltage insulation: resonant LLC versus MMC topology



$/kVA



How can SST support the energy transition?

Current challenges for the energy transition

- ➢ Supply chain constraints due to high demand for power transformers
- ➢ Required high grid infrastructure investments due to penetration of intermittent generation and load
- ➢ Increased occurrence of severe weather conditions to challenge grid equipment and operation
- ➢ Equipment to adapt to the reduction of grid inertia to maintain grid reliability
- ➢ Space constraints and transportation restrictions require high power density transformers

Datacenters

- Large MV transformers fleet (BTM)
- *Power quality* & integration of storage
- DC architecture enabler

C&I

- *Power quality*
- DER integration & grid services

Wind & Solar plants

- Efficiency of collector system
- DC architecture enabler

Distribution network

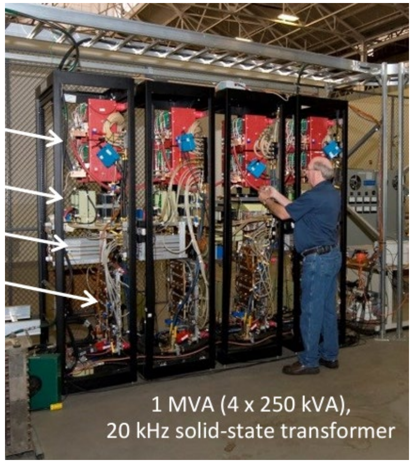
- *Power quality*
- EV charging station
- Power density

Transmission network

- Grid controls
- *Power quality*
- Modular design easy for transportation
- SS substations

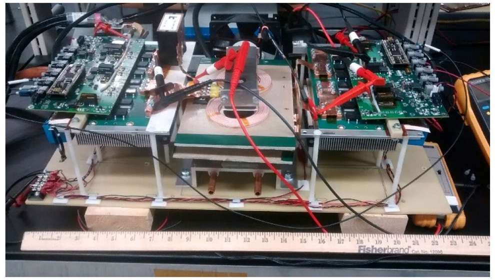
SST can improve grid performance while reducing the dependency to GOES and foreign suppliers

Experience in SST design and prototyping



1MVA, 13.8kVac – 265Vac
20kHz SST (2009)

1MW, 4.16kVac – 1kVdc
40kHz SST (2011)



150kVA, 1kVdc – 1kVdc
250kHz SST (2018)

1MW, 6kVdc – 1kVdc
200kHz SST (2020)

1MW, 6kVac – 690Vac
200kHz SST (2021)

SST need further development to meet stringent requirements for grid applications

Solid-state transformer

First 13.8kV/265V SST demonstration at GE Research using 10kV SiC devices (2009)

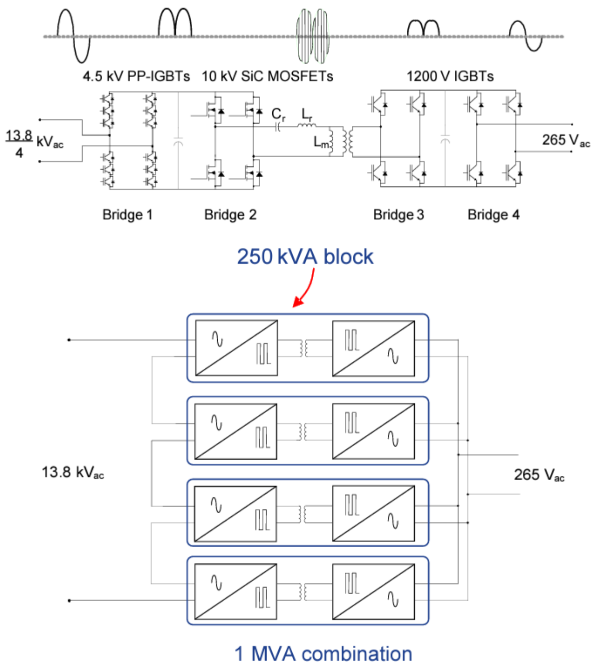


Fig. 3. Schematic of 250 kVA AC/AC block (top) and input-series

. 2. ~250 kVA transformers – 60 Hz dry-type (back), 20 kHz oil-filled er-cooled (front left) and 20 kHz dry-type forced-air cooled (front right).

Fig. 4. Back-to-back test setup with prototype SST cabinets and 60 Hz transformers.

A SST, being a substation by itself can retire many ancillary equipment in the grid

Acknowledgment

- The world's first flexible power transformer prototype development was sponsored by the US Department of Energy under the agreement DE-OE0000908

- The prototype was designed and manufactured by Prolec GE

- Cooperative Energy, Mississippi was the utility partner on the first field demonstration
  - installed and operate the flexible power transformer prototype at their Columbia substation. The transformer is still in operation and has a design service life of 40 years.

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