High-temperature transformers are key to grid resilience

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Agenda

- Overview of U.S. electrical power grid
- New regulations
- Role of high-temperature transformers in grid resiliency
- High-temperature transformer applications
- Fast-deployable transformers for grid resiliency
- Rapid recovery transformer initiative
- Conclusions

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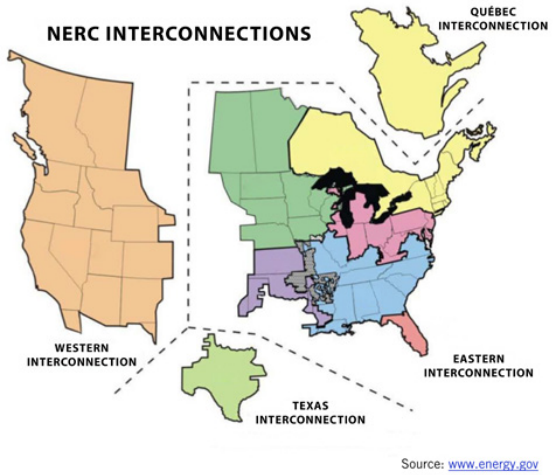
U.S. electrical power grid



Source: www.energy.gov

"National power grid" is really three interconnected regional grids

- More than 7,600 power stations
- 80,000 miles of EHV transmission lines
- 90% of electricity passing through EHV transformers

Operated by 3,000 utilities

Equipment of widely differing

Ages
Voltages
Capacities

Needs expansion and upgrades

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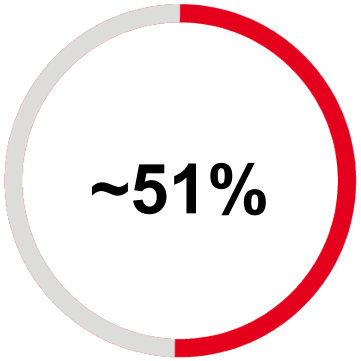
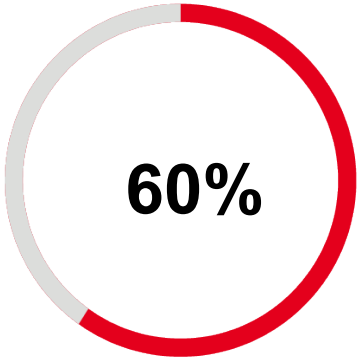
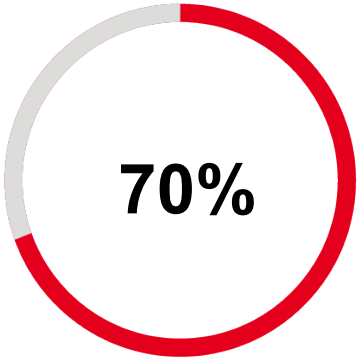
Aging infrastructure of U.S. electrical power grid



of U.S. generating capacity in plants at least 36 years old



of circuit breakers are 30+ years old



of transmission lines and power transformers are 25+ years old

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Power outages on the rise

3 of the 5 massive U.S. blackouts occurred since 2004*

Power outages were up 67% from 2011 to 2014

On average, ~500,000 people are affected daily by power outages*

58% of U.S. power outages due to severe weather**:

- Thunderstorms
- Hurricanes
- Blizzards

*Lexington Institute Report

**U.S. Department of Energy, Form OE-417, as cited in “Economic Benefits of Increasing Electric Grid Resilience to Weather Outages” report dated August 2013

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Power outages on the rise (continued)

Other causes of power outages:

- Equipment malfunctions, circuit overloads and load shedding**
- 20% of sustained outages (lasting >1 minute) caused by failing electrical equipment
- Headline quote: “Delta system failure marks wake-up call for airline industry”

Estimated annual cost at least $150 billion***

**U.S. Department of Energy, Form OE-417, as cited in “Economic Benefits of Increasing Electric Grid Resilience to Weather Outages” report dated August 2013

***According to the Galvin Electricity Initiative

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Power transformer—A critical component

Critical to the reliable operation of the electrical power grid

Failure of a single unit can:

- Cause temporary service interruption
- Lead to collateral damage

Custom-designed equipment

- Costs millions of dollars
- Is not interchangeable

Weigh hundreds of tons—too heavy to move by truck

Difficult to quickly replace

- Lengthy procurement
- 12 to 24 months

Designed for 25 to 35 years service

- Average age today is ~42 years

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Homeland Security identifies vulnerability

Average age of substation transformers is beyond designed life

Vandalism/terrorist activity

Extreme weather/global warming

- Heavy rains/rising ocean → flooding
- Heat waves/forest fires
- Higher ambient temperatures
- Hurricanes/tornadoes/severe storms
- Geo-magnetic and pulse disturbances

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Presidential Policy Directive 21

Critical infrastructure security and resilience

Issued February 12, 2013

Identifies 16 critical infrastructure sectors

Defines resilience as:

"the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

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FERC ordered development of physical security standards

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

In 2014, Federal Energy Regulatory Commission (FERC) took action to enhance grid resilience

FERC directed North American Electric Reliability Corporation (NERC) to:

- Develop reliability standards
- Require owners/operators of bulk-power system to address risks due to physical security threats and vulnerabilities

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High-temperature transformers play key role in grid resiliency

High-temperature liquid-immersed transformers offer possibility of:

Increased capacities for replacement units

- Same size
- Matching terminations

Unprecedented mobility

- Even very large capacity
- Emergency replacement

True step-change in design strategy

- Life extension
- Increased capacity
- Lighter weight

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High-temperature liquid-immersed transformers

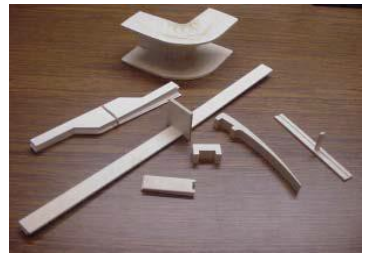
DuPont™ Nomex® insulation celebrated 50 years in 2017

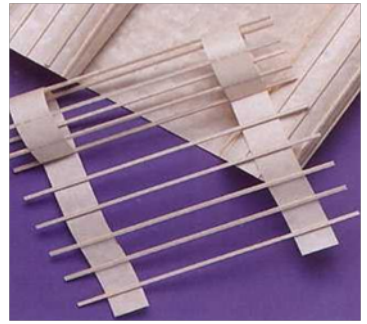
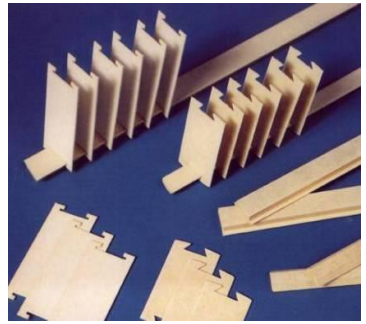
Long history of proven performance—40+ years

Recent global standards (IEEE and IEC) help guide development

Insulation offering expanding—widest selection in years

Use of high-temperature insulation expected to continue to expand to meet grid resiliency needs



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High-temperature transformer applications

Photo by Tamini Transformatori Srl

Photo by ABB

Photo by CG Power Systems, Belgium

Photo by ABB

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Typical mobile substations

For temporary or emergency use

Less than 100 MVA

Full hybrid insulation system

- 65/95°C top oil/average winding rise
- High-temperature wire insulation, spacers and strips
- Highest capacity for road weight limit

Mixed hybrid insulation system

- 65/75°C top oil/average winding rise
- High-temperature wire insulation only

Photo by Delta Star, Inc

Photo by CG Power Systems, Belgium

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Substation transformer in Seoul, South Korea

Situation

Bridge collapse forces switch from three 1-phase units due to reduced weight limits on city bridges

Challenges included

- Weight limits
- Need for increased capacity

Solution

- 60 MVA, 138 kV liquid-immersed transformer
- Nomex® hybrid insulation system
- Full hybrid insulation allows single 3-phase unit to meet weight limits

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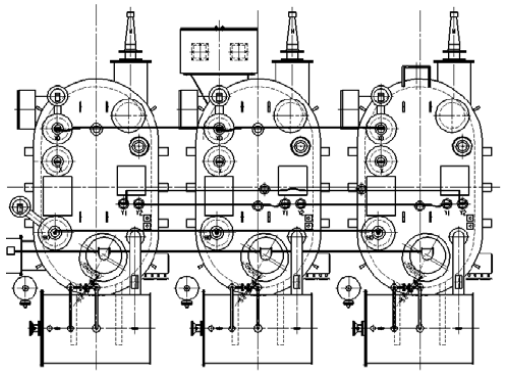
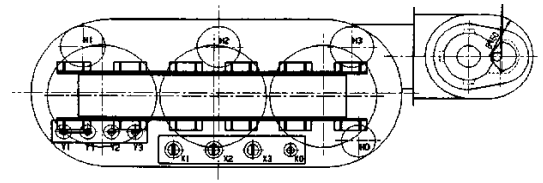
Comparison of three 1-phase units vs. single 3-phase unit





	Conventional 3x1 PH 20 MVA	Light weight 3PH 60 MVA
Transformer	22.35 ton per 20 MVA TR	28.8 ton
Tractor	8.5 ton	6.76 ton
Trailer	6.3 ton	4.37 ton
Total weight	37.15 ton per 20 MVA TR	39.93 ton
Length	5,050 mm	4,060 mm
Width	2,610 mm	2,500 mm
Height	3,500 mm	3,080 mm
Core loss	63 kW (20 MVA x 3)	26 kW
Copper loss	396 kW (20 MVA x 3)	470 kW
Total loss	459 kW (20 MVA x 3)	496 kW
Winding temp	65K	95K
Oil temp	55K	65K

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Compact transformer for urban substation in Grenoble, France

Situation

Aging 10 MVA transformer
in densely populated city center
needed to be replaced

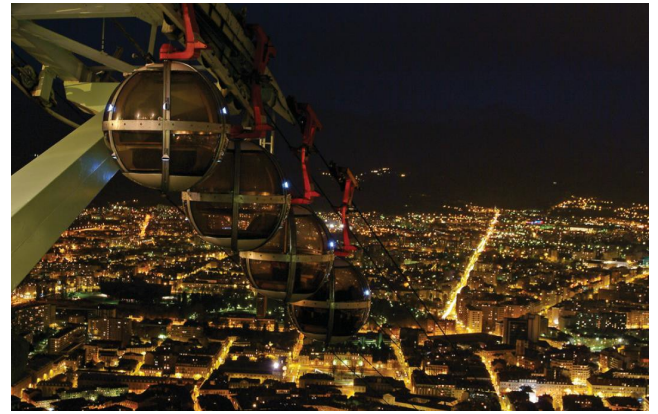
Challenges included

- Need for significantly increased capacity
- Compact size to fit in existing substation
- Very low noise requirement for residential district

Solution

- 36 MVA liquid-immersed transformer
- Natural air ventilation
- Nomex® hybrid insulation system

Photo by CG Power Systems, Belgium



Gaz Electricité de Grenoble (GEG)

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Interconnecting transformer

Photo by ABB

Photo by ABB

ESCELSA: 3-phase ABB hybrid power transformer		
Rated power (emergency)	MVA	300 (380)
Rated voltages (BIL)	kV	230/138-138/13.8
HV BIL	kV	1,050
Top oil temp rise	K	65
Avg wdg temp rise	K	65 (95)
Total mass	Tons	330

- Overloadable grid transformer
- Unit in place since 2003
- Installation: Brazil

Photo by ABB

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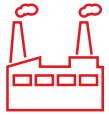
Building on the past to address grid resiliency

Long history of proven successes for substations and mobile substations

- Natural to use high-temperature transformers
- As response to challenge of grid resiliency

High-temperature insulation

- Expanding selection
- Helping enable innovative transformer designs



Multiple manufacturers exploring new solutions to meet grid resiliency needs

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First 250 MVA, 400 kV fast-deployable transformer

Situation

Power utility in Spain needed new design concept

- Fast-deployable emergency replacement units
- Needed larger capacity
- Replace existing 117 MVA

Challenges included

- Compact size
- Reduced weight
- Easier shipping by standard truck
- Increased capacity
- Need for reduced installation time

Solution

- 1-phase, shell type HV network transformer
- DuPont™ Nomex® hybrid insulation system
- Experimental installation at a power transmission grid on Mediterranean coast
- Operating successfully since 2012

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Fast-deployable network transformer in Spain

Photo by ABB

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Fast-deployable transformer—Size reduction example

	Standard substation transformer	Conventional fast-deployable transformer	Hybrid insulation fast-deployable transformer
Rated power (p.u.)	1	0.6	1.25
Load losses (p.u.)	1	0.87	1.74
No load losses @100% exc. (p.u.)	1	0.60	0.77
Shipping weight (p.u.)	1	0.53	0.62
Ratio ton/MVA	0.57	0.51	0.28
Shipping dimensions LxWxH (p.u.)	1 x 1 x 1	1.17 x 0.68 x 0.75	1.32 x 0.69 x 0.71
Overall dimensions LxWxH (p.u.)	1 x 1 x 1	0.94 x 0.85 x 0.80	0.93 x 0.76 x 0.79

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Rapid recovery transformer initiative

Consortium formed over past decade

U.S. Department of Homeland Security (DHS) Science & Technology Directorate (S&T)

Electric Power Research Institute (EPRI)

CenterPoint Energy, an energy delivery company headquartered in Houston, Texas

ABB, a global leader in power and automation technologies

Goal

To increase resilience of nation's electric transmission grid by drastically reducing recovery time associated with transformer outages

Design principle

Make the unit modular, transportable and quick to install

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Rapid recovery transformer—RecX prototype

Designed to replace the most common EHV transformers used by utilities

Solution

- Three 1-phase transformers
- Nomex® hybrid insulation system chosen to reduce both size and weight
- 345 kV at 200 MVA each
- Weighs 63 tons (vs. 100 to 400 tons for current power transformers)
- Shipped dry on lowboy flatbed trucks without accessories

Installation

- Five days total from factory to energized
- Tested and evaluated for >1 year at CenterPoint Energy substation in Texas

Rapid recovery transformer—RecX

Photo by ABB

Photo by DHS S&T

Photo by ABB

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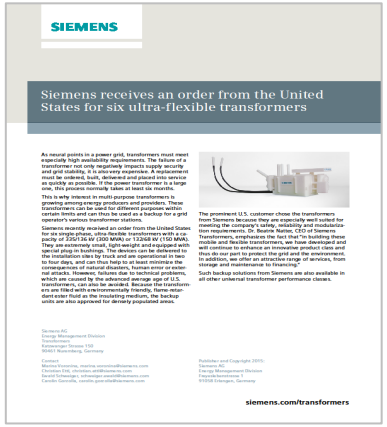
Siemens grid resiliency solutions

Siemens Transformers globally launched its resiliency concept “Pretact™” at the 2016 Hannover Fair

First order was for six ultra-flexible units for a major utility in the U.S.

- 335/136 kV at 100 MVA each
- Nomex® hybrid insulation system
- Extremely small and lightweight
- Deliverable by truck
- Operational in 2 to 4 days



siemens.com/transformers

siemens.com/transformer-resiliency

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Conclusions

Driving need for development of contingency plans

- Aging infrastructure → more frequent/more severe outages
- Increasing consumption
- New regulations

High-temperature, liquid-immersed transformers will play a key role in grid resiliency plans for many utilities

- Increased reliability
- Higher capacity
- Higher power density in urban size-restricted locations

Nomex® high-temperature insulation

- Offers new avenue to explore needs of power grid transformation
- Provides opportunity for true step-change in design strategy
  - Life extension
  - Increased capacity
  - Smaller size
  - Lighter weight

Expect to see many more applications for lighter or smaller transformers in the near future

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Learn more about Nomex® in high-temperature applications

Read the following case studies at **nomexpaper.dupont.com**

- Compact Transformer for Urban Substation in Grenoble
- ABB's First 250 MVA, 400 kV Fast-Deployable Transformer
- Rapid Recovery Transformer—RecX

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