Geomagnetic Storms and Standard TPL-007-1

Information and discussion meeting on Hydro-Québec transmission system planning

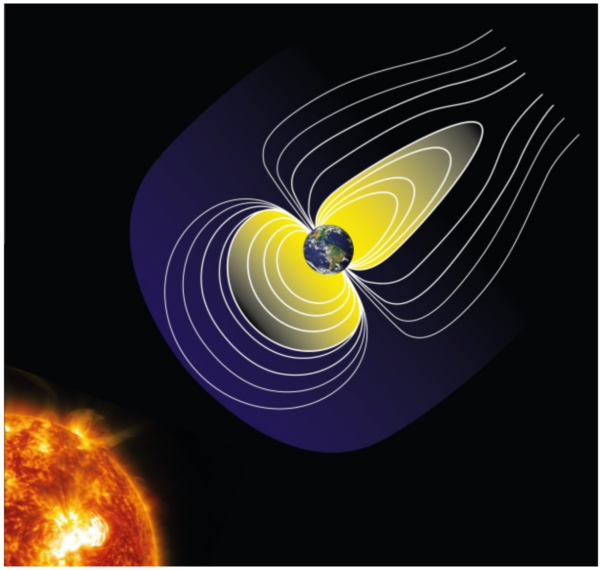
September 29, 2017

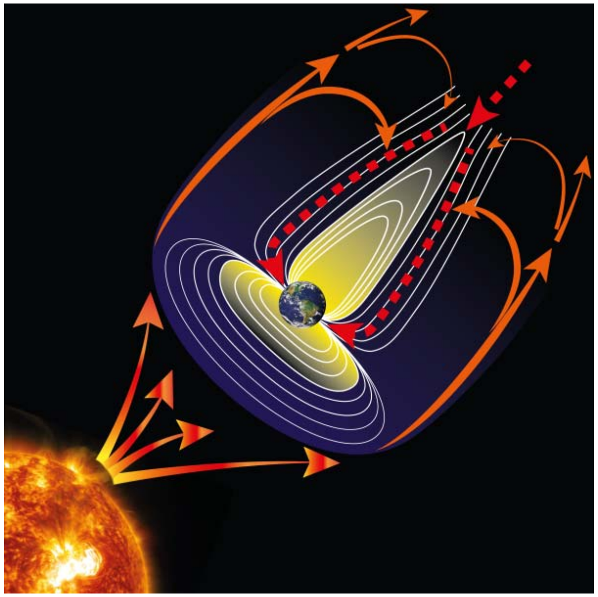
Outline

- What are geomagnetic storms?
- Impacts on transmission systems
- Hydro-Québec's work on geomagnetic storms
- NERC Standard TPL-007-1
- Upcoming changes in the standard (TPL-007-2)
- Conclusion

What are geomagnetic storms?

- A sudden burst of particles (mainly electrons and protons) from the sun
- Speeds of 200 to 1,000 km/s
- Particles are deflected by the Earth's magnetic field but then accelerated toward the Earth by a magnetic reconnection.
- A storm can be detected about ~48 hours in advance.
  - A network of probes and satellites gives an index of the storm's strength (Kp-index).
  - Actual severity detected only an hour ahead.
  - The impact on the power system is difficult to predict.





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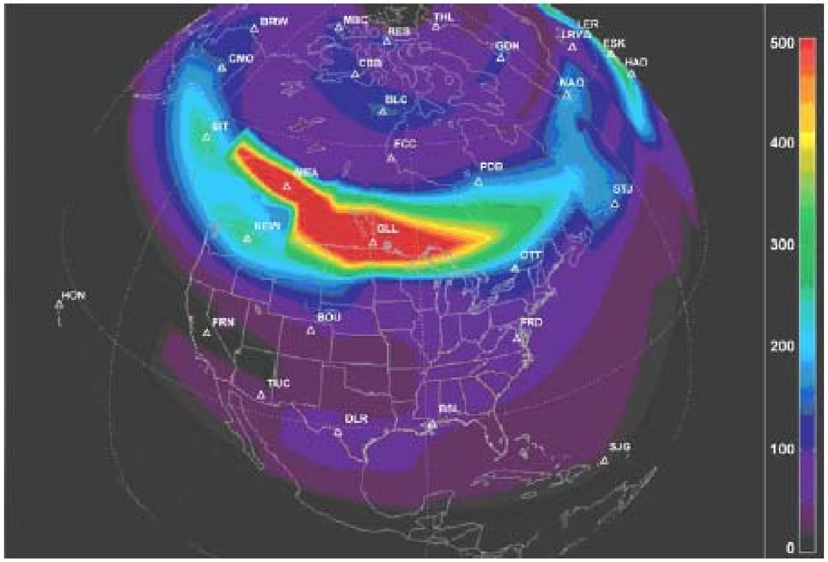
What are geomagnetic storms?

- The particles generate a high current in the ionosphere (≈100 km) (electrojet).

- The electrojet produces the northern and southern lights.

- The strength of electrojet currents is measured by ground-level magnetometers (Earth's magnetic field reading).



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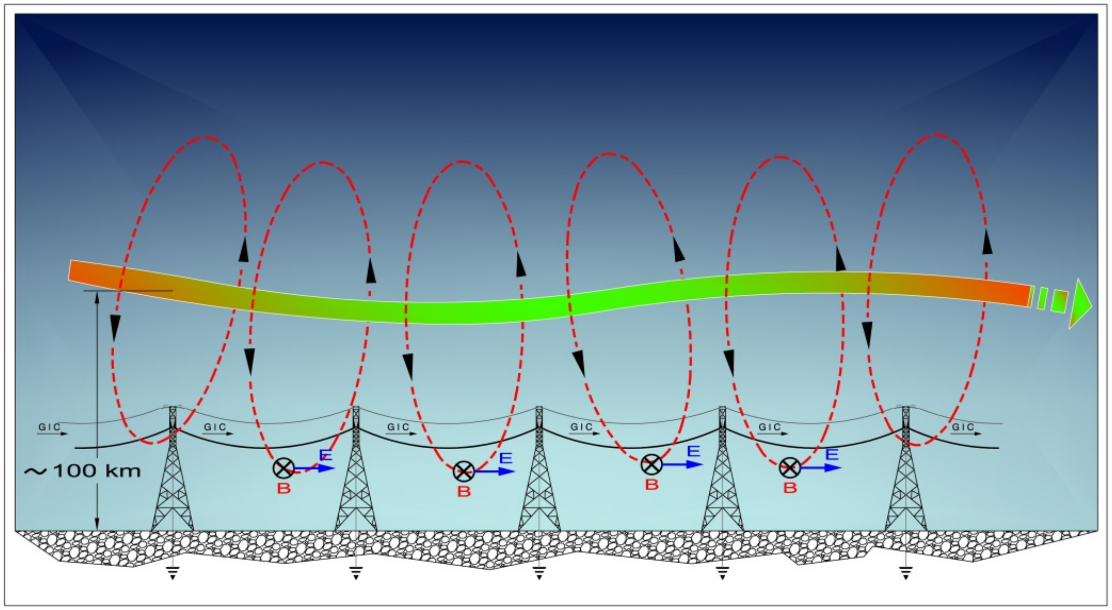
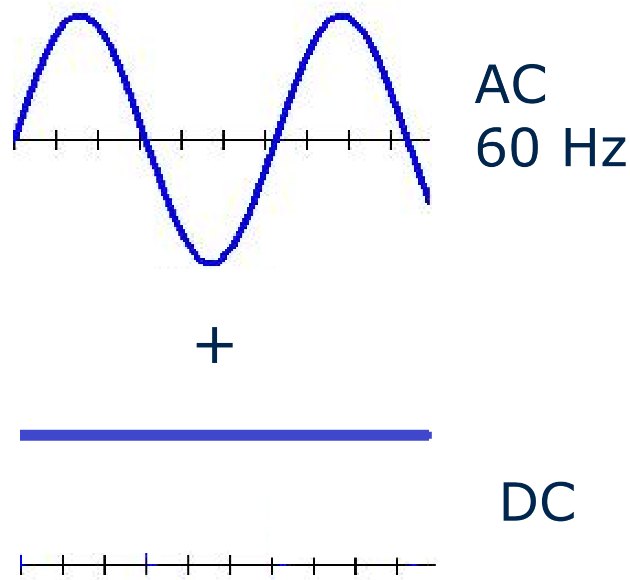
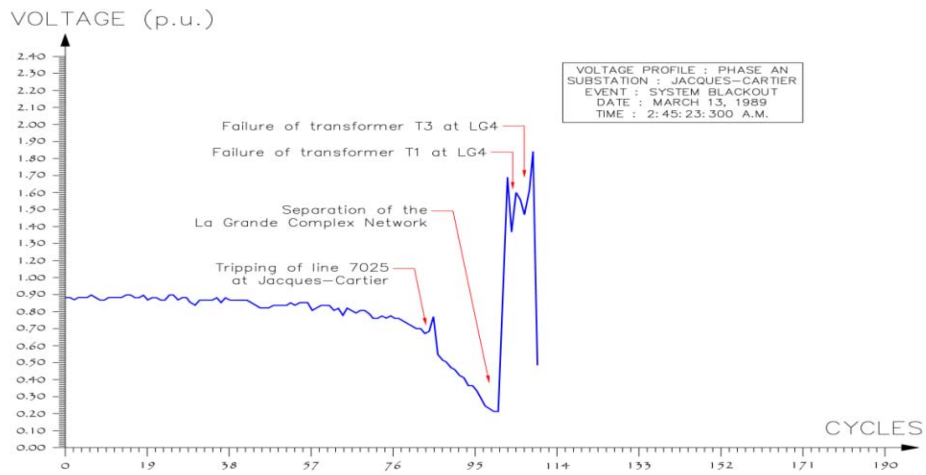
Impacts of geomagnetic storms





- The electrojet induces electric fields at ground level.
- The electric field creates direct current in transmission lines flowing via the neutral of grounded equipment.
- The direct current (DC) particularly affects transformers, making them work beyond their normal operating range (transformer saturation).

Impacts of geomagnetic storms

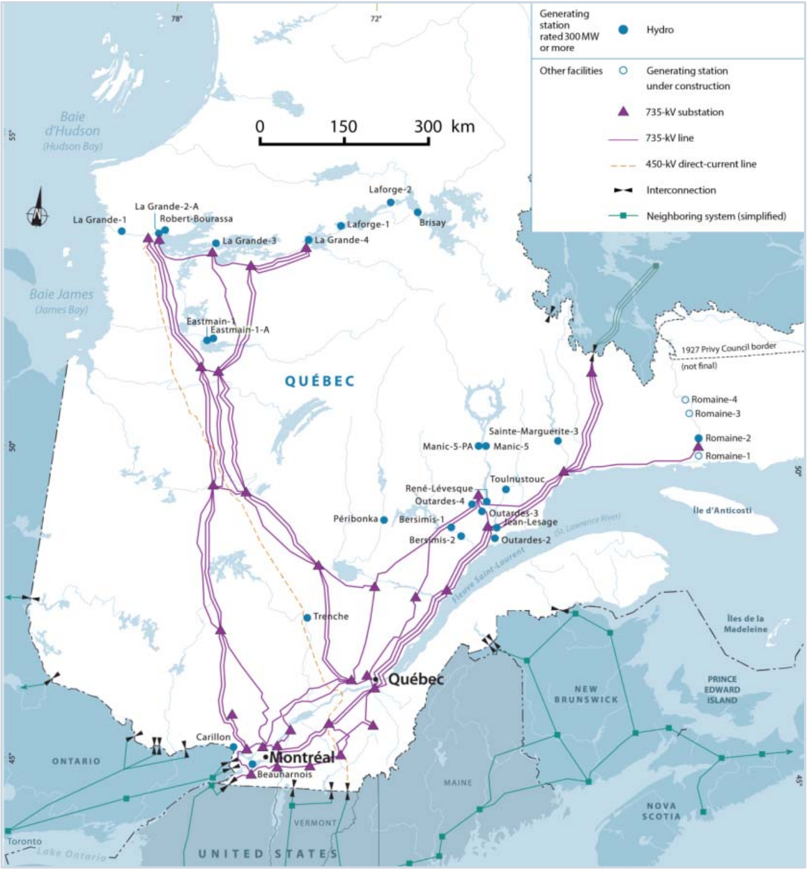


- Potential impacts on the power grid are as follows:
  - Harmonic currents and voltage distortion
  - Difficulty in adequately controlling voltage levels
  - Loss of or damage to equipment like transformers and capacitors
  - Malfunctioning of conventional and special protection systems (SPSs)

Impacts of geomagnetic storms

Hydro-Québec grid blackout due to the 1989 geomagnetic storm

- From March 12 to 14, a series of events occurred on the grid due to geomagnetic storms.
- Voltage collapse brought the entire grid down on March 13 at 2:45 a.m.
- This was hastened by the tripping of static var compensators, which help maintain system voltage.
- Full restoration took 9 hours.



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Impacts of geomagnetic storms

Major geomagnetic storms on record

- September 1859 – Carrington Event
  - Northern lights visible down to Cuba!
  - Telegraph down for two days in North America and Europe
  - Reports of reading a newspaper in New York in the dead of night!
- March 1989 – “Hydro-Québec Blackout”
  - To date, the largest impact of a geomagnetic storm on a power system
- March 1991– Storm similar to that of March 1989
  - New protection settings on static var compensators
  - No events on the Hydro-Québec system
- October 2003 – Halloween storm
  - Power system down in southern Sweden
- July 2012 – Missed storm
  - Storm larger than that of March 1989 occurred
  - Its trajectory missed the Earth

Work on geomagnetic storms

- Analysis of the causes of the 1989 blackout
  - Changes to static var compensator protections

- Additional equipment and SPSs for system reliability, which are also effective for geomagnetic storms
  - Series compensation on 735-kV lines
  - Automatic switching of shunt reactors
  - Additional static var compensators
  - Undervoltage load shedding SPS

- Installation of geomagnetic storm measuring systems
  - DC current measured at the compensator transformer neutral and voltage distortion measured at certain power system facilities

Work on geomagnetic storms

Operating directives implemented during geomagnetic storms

- Storm forecasting and real-time monitoring
  - Based on alert providers and distortion measurements taken on the power system
- Equipment redeployment
  - Power system elements that are effective against geomagnetic storms redeployed when a storm is announced
- Reduced power flows
  - Reduced stress at certain sensitive locations of the grid during a storm

Kp	Geomagnetic latitude	Auroral activity
0	66.5° or higher	Very low
1	64.5°	Low
2	62.4°	Low
3	60.4°	Unsettled
4	58.3°	Active
5	56.3°	Minor storm
6	54.2°	Moderate storm
7	52.2°	Strong storm
8	50.1°	Severe storm
9	48.1° or lower	Extreme storm

Work on geomagnetic storms

- Studies at IREQ, Hydro-Québec's research institute
  - Static var compensators and their protections
  - DC current in power transformers
  - Electric field measurements in Abitibi on retired telephone lines

- Recent work
  - Participation in NERC committees on geomagnetic storms
  - Simulation of a geomagnetic storm on the entire Hydro-Québec grid

Standard TPL-007-1

- Following a FERC order in May 2013, NERC is put in charge of drafting standards on geomagnetic storms.
  - **Operating standard** (EOP-010-1): Develop and implement operating plan to mitigate the effects of geomagnetic disturbances. (Effective April 2015)
  - **Planning standard** (TPL-007-1): Consider geomagnetic storms in transmission system planning. (Effective January 2017)
- TPL-007-1
  - Evaluation every five years
  - Consider a benchmark geomagnetic storm of high magnitude (statistically the 1 in 100-year storm)
  - Apply that storm to the power system, conducting two impact assessments:
    - Impact on the grid (voltage collapse and loss of power system)
    - Impact on transformers (damage due to temperature rise)
- Régie de l’énergie enforces NERC standards
  - TPL-007-1 has not yet been adopted by the Régie but Hydro-Québec applies it on a voluntary basis.

NERC Standard TPL-007-1

R1 – Identify roles and responsibilities
(6 months)

R2 – Maintain a data model for conducting subsequent studies
(18 months)

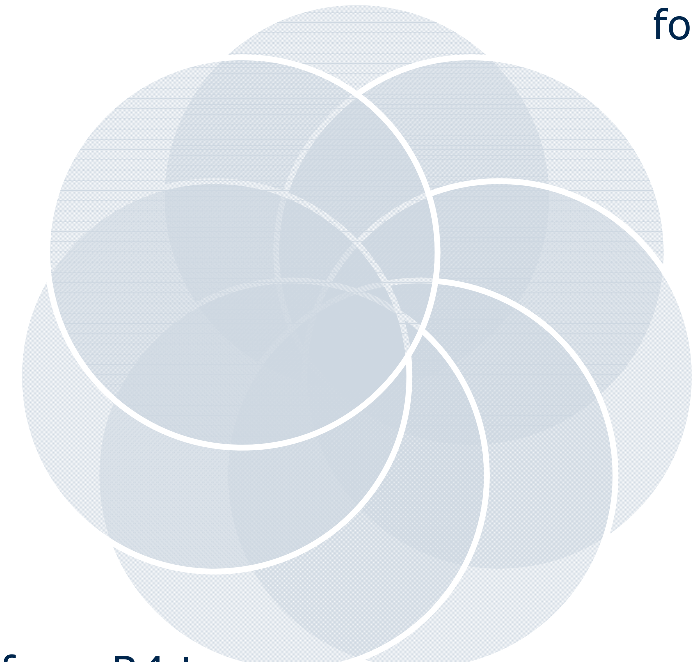
R3 – Set a criterion for acceptable system steady-state voltage during the benchmark storm
(60 months)

R4 – Assess geomagnetic storm vulnerability using the benchmark storm
(60 months)

R5 – Provide results from R4 to transformer owners
(≥ 200 kV, GIC 75 A/phase)
(24 months)

R6 – Evaluate transformer temperature rise (owner or manufacturer)
(48 months)

R7 – Develop a corrective action plan
(60 months)



NERC Standard TPL-007-1

- R1 – Identify roles and responsibilities (6 months – July 2017)
  - Consists in establishing the individual and joint responsibilities of the planning coordinator (PC) and transmission planner (TP) in the PC planning area with respect to maintaining models and conducting the studies needed to complete geomagnetic disturbance (GMD) vulnerability assessments
  - For R1, roles and responsibilities are established within Hydro-Québec

NERC Standard TPL-007-1

- R2 – Maintain a data model for conducting subsequent studies (18 months – July 2018)

  - Maintain a system model for the planning area for conducting the studies needed to complete GDM vulnerability assessments.

  - The data is specified in the document "Transmission System Modeling Data Requirements and Reporting Procedures".
    - http://www.hydroquebec.com/transenergie/en/pdf/hqt-modelling-requirements.pdf
    - Every TO and GO must provide, for the transmission facilities involved, the modeling data needed to calculate DC currents during geomagnetic storms.

NERC Standard TPL-007-1

R2 – (Cont.) Modeling data for geomagnetic storms

Transmission system element	Modeling data

Transmission substations	• Substation ground grid resistance (Ω)
	• Substation geographic coordinates
	    • Latitude (positive for North, negative for South)
	    • Longitude (positive for East, negative for West)

Transmission lines	• DC resistance (Ω/phase)
	• Coordinates of taps on lines
	    • Latitude (positive for North, negative for South)
	    • Longitude (positive for East, negative for West)
	• Presence of overhead ground wires and counterpoise wires

Transformers (voltage and phase shifting)
 	
(if any winding voltage > 200 kV and any transformer connection is grounded)
	• DC resistance (Ω/phase) for each winding
	• Core design
	    ○ three-phase shell
	    ○ Single core
	    ○ 3-phase 3-legged
	    ○ 3-phase 5–legged
	    etc.
	• Factor relating reactive power losses to DC current in the transformer (K factor)
	• Grounding resistance (Ω)
	• Presence of DC current blocking mechanism in the neutral

Shunt reactors	• DC resistance of winding (Ω/phase) • Grounding resistance (Ω)

NERC Standard TPL-007-1

- R3 – Set a criterion for acceptable system steady-state voltage during the benchmark storm (60 months – January 2022)
  - For system planning, during simulations, voltage levels on the transmission system must be monitored.
  - If geomagnetic storm simulations lead to voltages beneath acceptable levels, corrective actions must be taken.

NERC Standard TPL-007-1

- R4 – Assess geomagnetic storm vulnerability using the benchmark storm (60 months – January 2022)
  - Using the modeling data for geomagnetic storms (R2)
  - A benchmark storm is applied to the power system
    - A storm with a 100-year recurrence period based on statistical studies
    - Makes it possible to find the DC currents that the storm creates in the system
    - Those currents act as input for transformer thermal assessment (R5)
    - The effect of such currents on the power system is then simulated
      - Transformer saturation causes voltage sag, and system voltage and current distortion

NERC Standard TPL-007-1

- R5 – Provide DC current results (R4) to transformer owners (24 months – January 2019)

- Rule of thumb in the standard, to simplify which transformers must be assessed
  - Based on worst-case simulations and IEEE temperature rise standards

- Study requested for transformers with:
  - High-side voltage ≥ 200 kV
  - Connected by the neutral point
  - DC current > 75 A/phase found in the vulnerability study (R4)

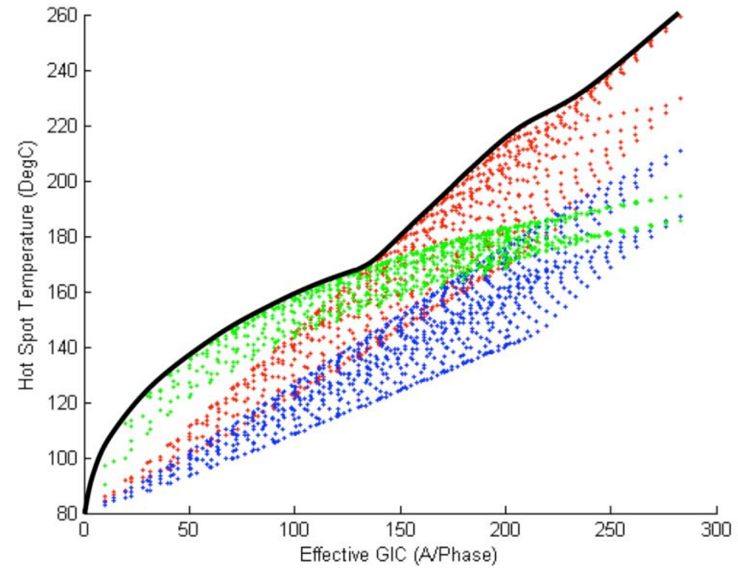


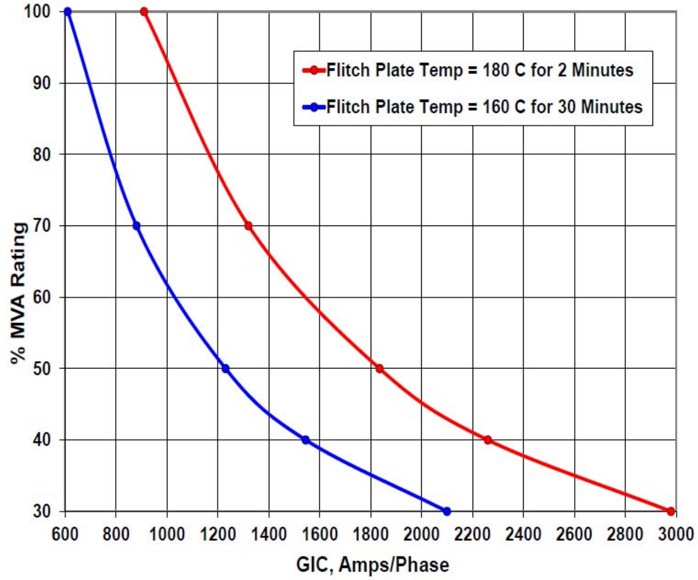
TABLE 1:
Excerpt from Maximum Temperature Limits Suggested in IEEE C57.91-2011

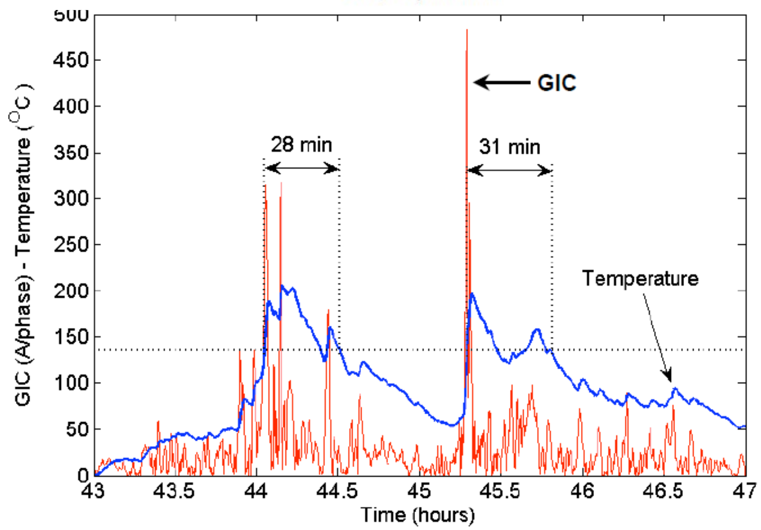
	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-time emergency loading	Short-time emergency loading
Insulated conductor hottest-spot temperature °C	120	130	140	180
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	150	160	200
Top-oil temperature °C	105	110	110	110

NERC Standard TPL-007-1

R6 – Evaluate transformer temperature rise (owner or manufacturer) (48 months – January 2021)

- Study to demonstrate that transformers can withstand the benchmark storm without damage
- A number of methods are proposed:
  - DC current curves provided by the manufacturers
  - Simulation with a thermal model
  - Other models that can be technically demonstrated as equivalent



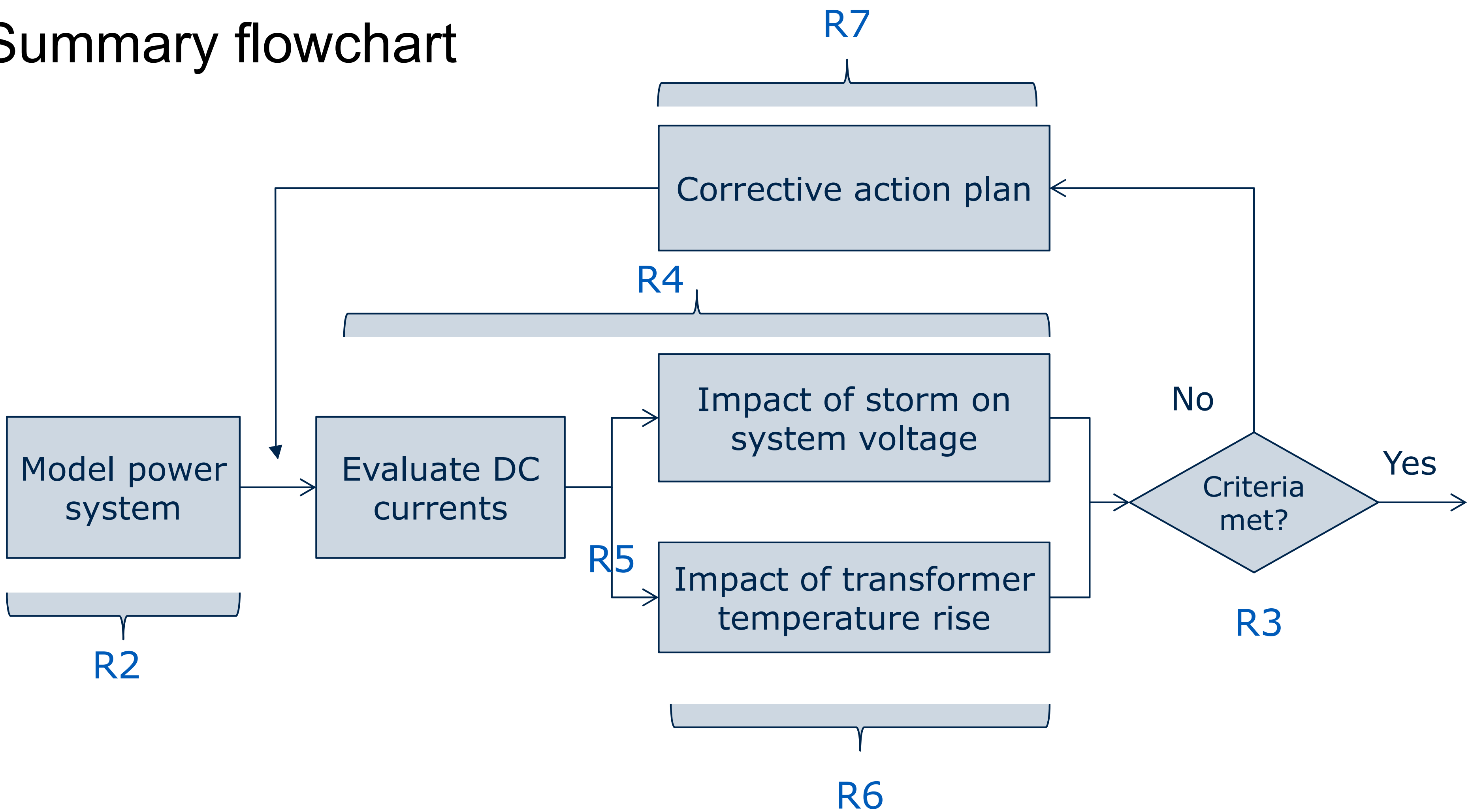


NERC Standard TPL-007-1

- R7 – Develop a corrective action plan (60 months – January 2021)
  - After the vulnerability assessment for system voltage and transformer temperature rise (R5 and R6)
  - If the voltage criteria (R3) are not met
  - Corrective actions reiterated until the criterias are met
  - Corrective actions may include:
    - Adding equipment
    - Modifying operating directives
    - Adding protection systems or SPSs

NERC Standard TPL-007-1

Summary flowchart



NERC Standard TPL-007-2

- TPL-007-1 has been in force since January 2017 but FERC has asked NERC to review it to add:
  - A benchmark storm with a more severe local effect
    - Different way of interpreting the statistics
    - Extra assessment in addition to the benchmark storm
    - This more extreme assessment does not require developing a corrective action plan
    - Does not change what is already in the standard and in effect
  - Procedures for collecting magnetometer and DC current data in the planning area
  - Deadlines for implementing corrective actions after the TPL-007-1 assessment
    - 2 years if the corrective action does not require adding equipment
    - 4 years if equipment must be added
- Effective date for TPL-007-2 remains uncertain (before 2021?!)

Conclusion

- The new standards are concerned with power system resiliency.
- TPL-007-1 deals with the issues of geomagnetic storms affecting power systems.
- Hydro-Québec TransÉnergie as planning coordinator is in charge of enforcing this standard.
- Transmission and generator owners:
  - Must provide DC data for modeling the power system (R2)
  - Transformer temperature rise studies (R6) may be requested if the DC current exceeds 75 A/phase during those studies (R5)
  - Meetings of a more technical nature may be held with Hydro-Québec experts
- The NERC site on the standard and geomagnetic storms contains considerable information
  - http://www.nerc.com/pa/Stand/Pages/Project-2013-03-Geomagnetic-Disturbance-Mitigation.aspx

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Questions?