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Hydro One Hybrid Thermal Model for Ampacity Calculations of Bare Overhead Conductors in Steady State

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SUMMARY

Hydro One partnered with the Electric Power Research Institute (EPRI) in collaboration with the manufacturer Southwire Co. to develop a transmission line sensor project to collect direct measured parameters from line sensors in order to compare with theoretical thermal models.

The purpose of this paper is to validate the existing AMPAC line rating application against the model of the IEEE standard 738–2006 "IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors", and a modified version of the IEEE 738-2006 and AMPAC program designated as "hybrid" model. A vigilant sensitivity analysis on the main parameters used in these applications is essentially required. The intention is also to verify correctness of the Hydro One thermal model techniques for real time applications.

The methodology adopted in the study is to analyse and choose an optimized ampacity calculation method for different aerial conductor types under various weather conditions. Ampacity for different conductors is initially calculated using IEEE 738 and AMPAC algorithm using data provided by line sensors. Then, ampacity for same conductors is determined based on Hydro One predefined weather data such as wind speed, wind angle and ambient temperature. Finally, the results for each method are compared using statistical and sensitivity analysis.

The study also identifies the discrepancies between both algorithms by comparing the calculated ampacity under the same weather conditions based on field measurements such as temperature, wind speed and angle, solar radiation, and current through conductor, and proposes a new "hybrid" model that can be implemented for real time applications as well as for future ampacity calculations. High speed of the proposed "hybrid" model was verified to work in on-line monitoring systems and web applications without compromising system operation flexibility and outage planning.

The paper concludes that the "hybrid" algorithm determines an increased ampacity of approximately 3% to 6% on the existing 2250 high voltage transmission circuits at Hydro One for continuous and 15-minute thermal ratings. Therefore, an increased ampacity rating has the potential to increase the capacity of existing lines, determine considerable savings for future transmission expansions and defer expansion investment and generate more revenue on the existing installed equipment base.

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KEYWORDS

Current – Thermal modelling
Bare Overhead conductors
Real Time applications

1. INTRODUCTION

Ontario Hydro developed original Monograms to determine thermal ampacity to operate bare overhead conductors at Continuous ratings (initially 49°C) and Emergency ratings (limited to 90°C) and considering annealing, since 1953.

The first version of the in-house developed software to calculate thermal ratings on aerial conductors, named AMPAC, was implemented circa 1980.

In 2014, Hydro One partnered with The Electric Power Research Institute (EPRI) in collaboration with the manufacturer Southwire Co. to develop a transmission line sensor project in order to collect direct measured parameters from line sensors and weather stations in order to compare and validate thermal models based in the IEEE standard 738-2006 and Hydro One's AMPAC program.

The new AMPAC/IEEE 738-2006 hybrid algorithm has being successfully implemented for real time operation in Hydro One in 2019.

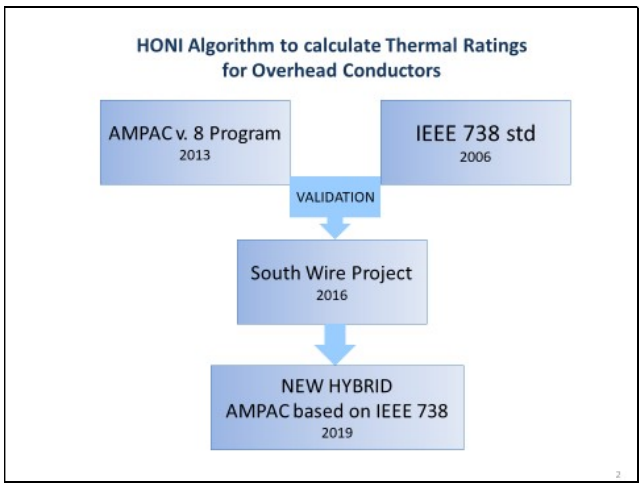


Fig. 1 AMPAC/IEEE 738-2006 hybrid model evolution

2. HYDRO ONE AMPAC and IEEE 738-2006 THERMAL MODEL DIFFERENCES

The main difference between both algorithms occur in several three areas [2]:

1. convection heat loss,
2. radiation heat loss,
3. solar radiation.

The AMPAC algorithm used theoretical principles of convective heat transfer by discretely calculating all air parameters (density, specific heat, expansion coefficient, viscosity) as well as Grasshof, Nusselt and Reynolds numbers. The new AMPAC algorithm, although based on the same principles, uses simplified formulas and parameters determined in experiments [2].

There is a difference in the implementation of the new AMPAC/IEEE 738-2006 hybrid algorithm. The biggest impact on the performance of the program have the numerical methods which are responsible for iterations required to take into account interactions between heat transfer and heat generation, namely variation of the resistance with the temperature [2].

Function	AMPAC [1], [2]	IEEE 738-2006 [4], [1]
Solar Heat Gain	$P_s = \alpha_s SD$	$P_s = \alpha_s Q_{se} \sin(\theta) A'; \quad \theta = \arccos[\cos(H_c)\cos(Z_c - Z_l)]$
Joule Heat Gain	$P_J = I^2 R_{ac}$ $for\ X < 1,\ R_{ac} = R_{dc}\left[1 + \left(0.00503 X^{3.9345}\right)\right]$ $for\ X < 2,\ R_{ac} = R_{dc} / \left[1.0777 - \left(0.07156 X\right)\right]$ $for\ X \geq 2,\ R_{ac} = R_{dc} / \left[1.2883 - \left(0.176 X\right)\right]$ $where\ X = 0.0501324\sqrt{60/R_{dc}}$	$P_J = I^2 R(T_c)$ *where* $R(T_c) = \left[\frac{R(T_{75^\circ}) - R(T_{25^\circ})}{T_{75^\circ} - T_{25^\circ}}\right](T_c - T_{25^\circ}) + R(T_{25^\circ})$
Forced Convective Heat Loss	$q_{cf} = 0.3048 \cdot \pi \cdot L_f \cdot Nu \cdot \Delta T$ $T_f = \frac{T_C + T_A}{2}$ $L_f = 0.0242 + 0.00007 \cdot T_f$	Forced convective loss is the larger of the two equations is used. At low wind speed, convective loss is the larger of forced and natural convection $P_{c1} = \lambda_f K_{angle}(T_s - T_a)\left[1.01 + 0.0372\left(\frac{D\rho_f V}{\mu}\right)^{0.52}\right]$ $P_{c2} = \lambda_f K_{angle}(T_s - T_a) 0.0119\left(\frac{D\rho_f V}{\mu}\right)^{0.6}$ *where* $K_{angle} = 1.194 - \cos(\delta) + 0.194\cos(2\delta) + 0.368\sin(2\delta)$
Natural Convective Heat Loss	$q_{cn} = 0.3048 \cdot (1.163 \cdot \pi \cdot L_h \cdot \Delta T \cdot ANu)$ $L_h = 0.02085 + 0.0000645 T_c$ $ANu = \frac{2}{A} \cdot \left(1 - \left(B \cdot \left(\sqrt{1 + \frac{1}{B}} - 1\right)\right)\right)$ $B = \frac{0.033}{\left(\lvert Gr \cdot Pr\rvert^{0.25}\right) \cdot \left(\log\left(1.0 + \frac{4.5}{\lvert Gr \cdot Pr\rvert^{0.25}}\right)\right)}$	$P_c = 0.0205 \rho_f^{0.5} D^{0.75} (T_s - T_a)^{1.25}$
Radiation Heat Loss	$P_r = 0.138 D\varepsilon\left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right]$	$P_r = 0.0178 D\varepsilon\left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right]$

Table 1 AMPAC and IEEE 738-200 thermal model

3. EPRI/SOUTHWIRE LINE SENSOR PROJECT

A total number of twenty six line sensors and three base stations were installed at three different Hydro One sites covering eight 115 and 230 kV transmission circuits across Ontario during 2015 and 2016. Telemetered values from line sensors and base stations were sampled every 5 – 6 minutes and transmitted to a Southwire stand-alone server. Southwire hosted the data and provided visualization to Hydro One through a secure web portal with regular data updates on a monthly basis.

While the performance of all of the base stations was satisfactory, the proto-type design of the line sensors performance showed high rate of failure of approximately 30% (defective 8 out of 26 sensors). Southwire identified some defects during the sensor installation as contributing factor.

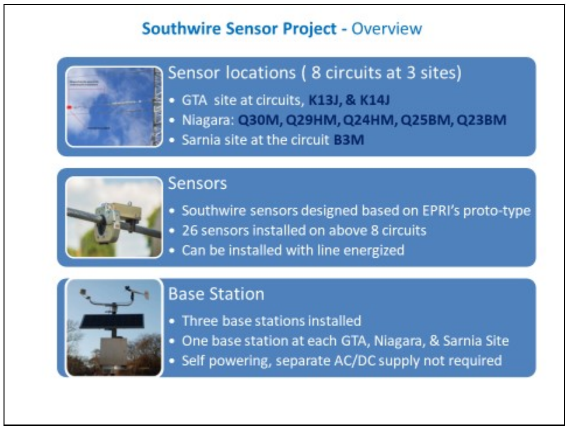


Fig. 2 Line Sensor Project Overview

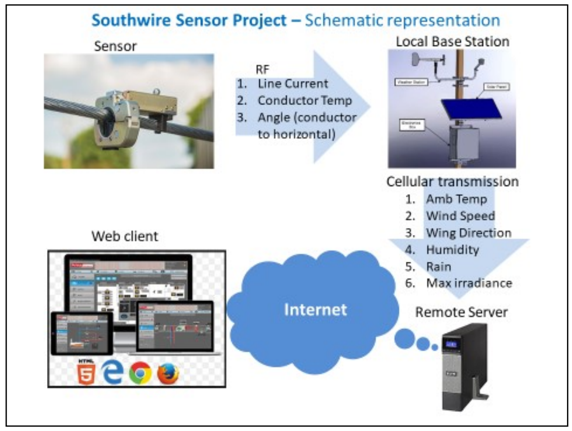
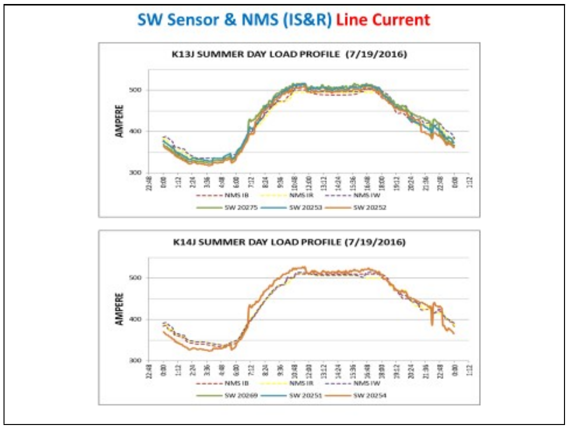


Fig. 3 Line Sensor Project Schematic

4. HYDRO ONE NMS (SCADA) and SOUTHWIRE SENSOR COMPARISON

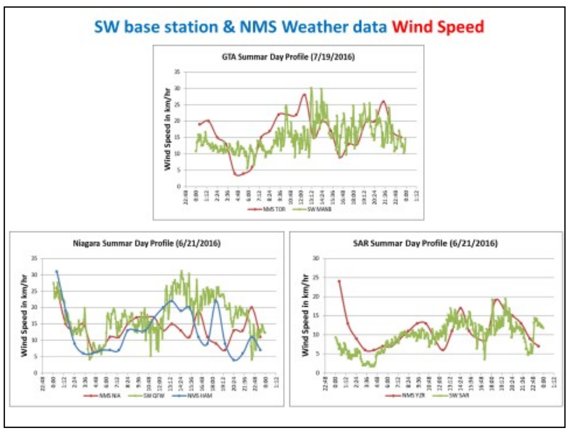


SW Sensor & NMS (IS&R) Line Current

SITES	CIRCUITS	SENSOR CURRENT SW DEVIATION FROM NMS SUMMER DAY in AMP (sample each 15-min)		
		Max AMP	Min AMP	Avg AMP
GTA	K13J	17.23	-19.52	1.44
	K14J	25.77	-28.96	1.46
NIAGARA	Q30M	60.70	-65.31	-5.31
	Q29HM	89.24	-45.00	17.42
	Q24HM	99.02	-44.43	16.40
	Q25BM	55.52	-64.12	-1.75
	Q23BM	41.90	-64.50	-4.69
SARNIA	B3N	379.73	-81.17	134.24
ALL SITES & CIRCUITS (except B3N)		99.02	-65.31	3.57

Fig. 4 Line Current Comparisons

Line sensor current profile match with NMS telemetry records, but the deviation at each circuit is not consistent. Post-installation precise iterative calibration is warranted.

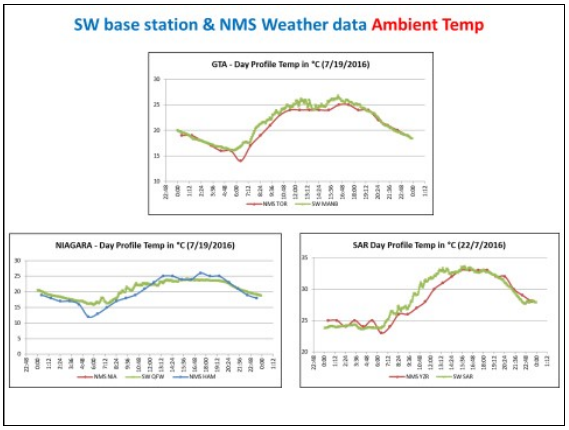


SW base station & NMS Weather data Wind Speed

SITES	CIRCUITS	SENSOR WIND SPEED SW DEVIATION FROM NMS in Km/h SUMMER DAY		
		Max Km/h	Min Km/h	Avg Km/h
GTA	K13J K14J	7.59	-9.66	-1.66
NIAGARA	Q30M Q29HM Q24HM Q25BM Q23BM	9.7	-9.95	-0.52
SARNIA	B3N	6.46	-18.41	-6.44
ALL SITES & CIRCUITS		9.70	-18.41	-1.53

Fig. 5 Wind Speed Comparisons

Wind speed is not uniform over the entire line, its distribution is geographical terrain dependent. It is hollow to compare measurements recorded at different locations.



SW base station & NMS Weather data Ambient Temp

SITES	CIRCUITS	SENSOR TEMPERATURE SW DEVIATION FROM NMS in °C SUMMER DAY		
		Max °C	Min °C	Avg °C
GTA	K13J K14J	2.81	-0.27	0.71
NIAGARA	Q30M Q29HM Q24HM Q25BM Q23BM	4.03	-2.33	0.51
SARNIA	B3N	3.79	-0.68	1.08
ALL SITES & CIRCUITS		4.03	-2.33	0.77

Fig. 6 Ambient Temperature Comparisons

The telemetered ambient temperature by the line sensors reasonably match with weather info from the nearby airports available in NMS.

5. HYDRO ONE AMPAC POLICY ON WIND SPEED AND WIND ANGLE

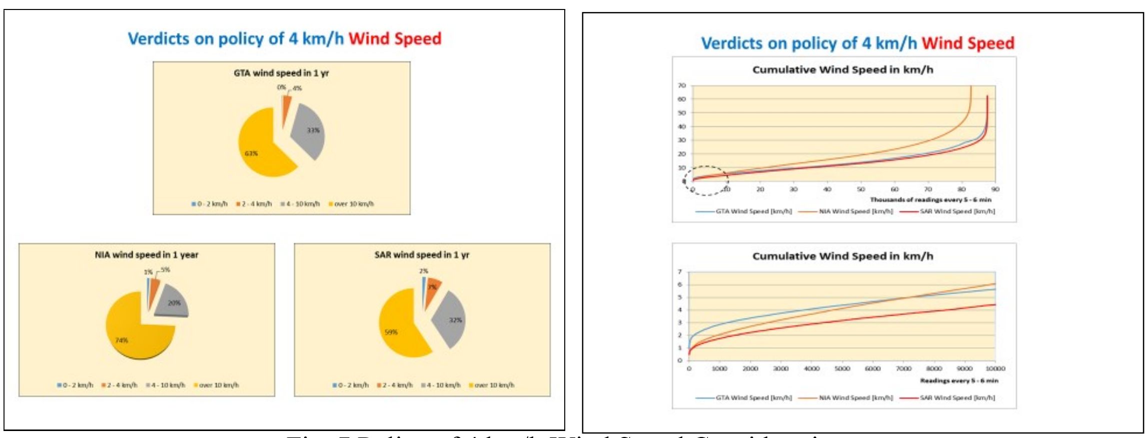


Fig. 7 Policy of 4 km/h Wind Speed Considerations

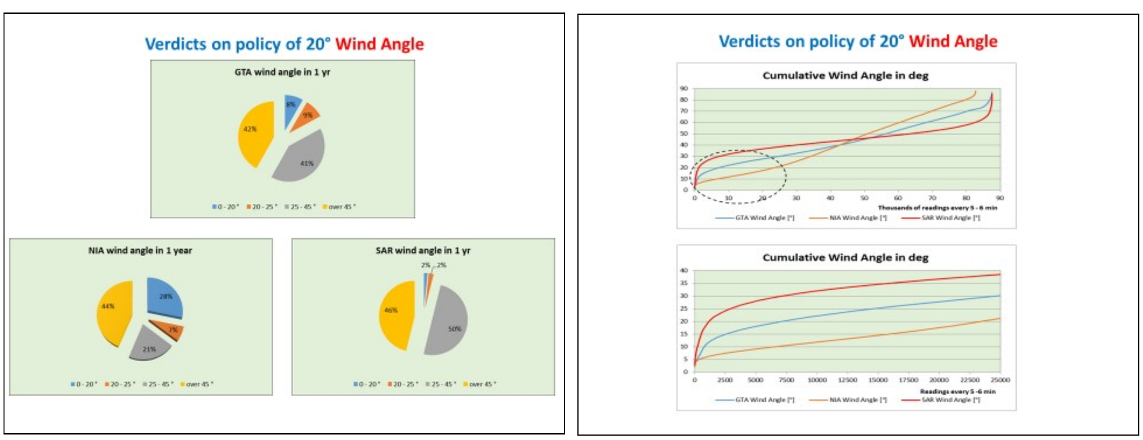


Fig. 8 Policy of 20° Wind Angle Considerations

Field measurements confirmed appropriateness of Hydro One policy of wind speed of 4 km/h and wind angle of 20° for thermal calculations.

6. SENSITIVITY ANALYSIS IN PLANNING FRAMEWORK

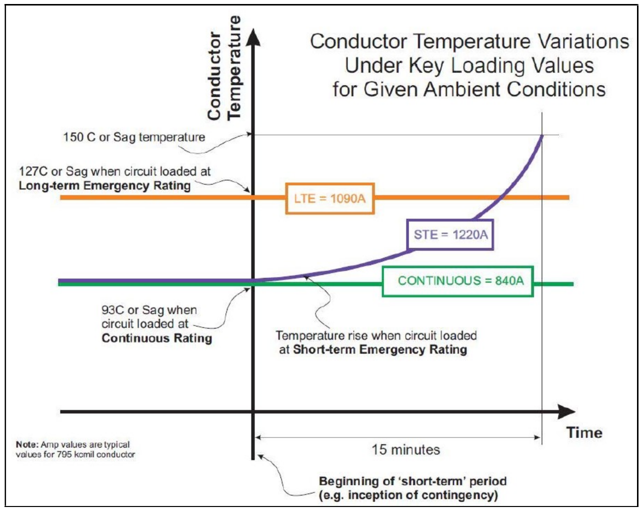


Fig. 9 Planning Criteria for Continuous and Emergency Thermal Ratings [3]

The following sensitivity analysis using IEEE-738 algorithm was performed to verify consistency with Hydro One planning criteria for continuous and emergency thermal ratings of bare overhead conductors.

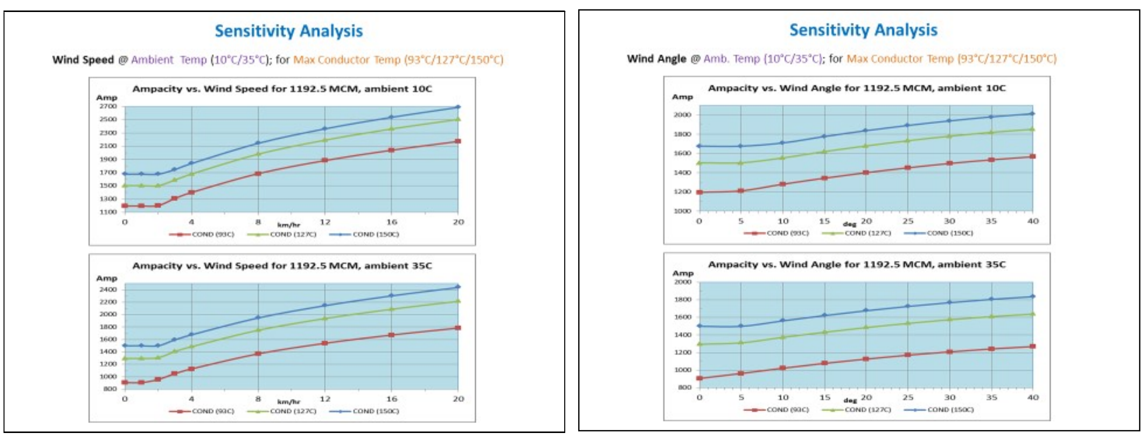


Fig. 10 Wind Speed and Wind Angle Sensitivity

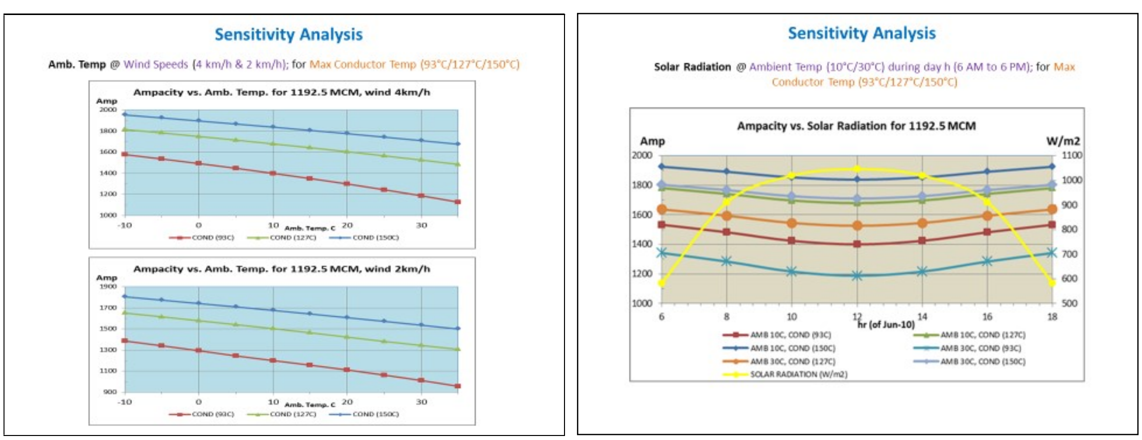
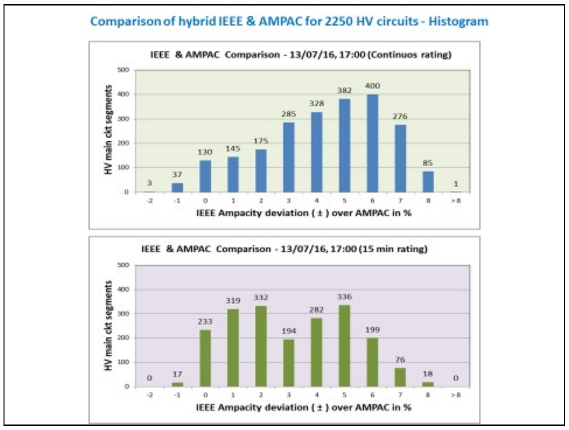
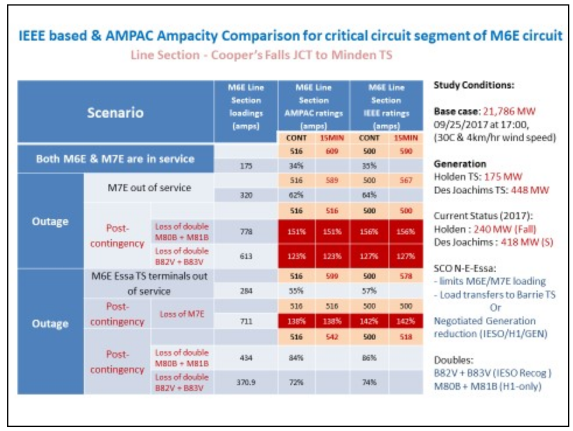


Fig. 11 Ambient Temperature and Solar Radiation Sensitivity

7. AMPAC/IEEE 738-2006 HYBRID MODEL IN REAL TIME OPERATION

Deviations between the AMPAC/IEEE 738-2006 hybrid and the old AMPAC algorithm were studied on 2250 main circuit sections that Hydro One operates at 115kV, 230 and 500 kV.





IEEE based & AMPAC Ampacity Comparison for critical circuit segment of M6E circuit
Line Section - Cooper's Falls JCT to Minden TS

Scenario			M6E Line Section loadings (amps)	M6E Line Section AMPAC ratings (amps)		M6E Line Section IEEE ratings (amps)	
				CONT	15MIN	CONT	15MIN
Both M6E & M7E are in service				516	609	500	590
			175	34%		35%	
Outage	M7E out of service			516	589	500	567
			320	62%		64%	
	Post-contingency			516	516	500	500
		Loss of double M80B + M81B	778	151%	151%	156%	156%
		Loss of double B82V + B83V	613	123%	123%	127%	127%
Outage	M6E Essa TS terminals out of service			516	599	500	578
			284	55%		57%	
	Post-contingency	Loss of M7E		516	516	500	500
			711	138%	138%	142%	142%
	Post-contingency			516	542	500	518
		Loss of double M80B + M81B	434	84%		86%	
		Loss of double B82V + B83V	370.9	72%		74%	

Study Conditions:

Base case: 21,786 MW
09/25/2017 at 17:00,
(30C & 4km/hr wind speed)

Generation
Holden TS: 175 MW
Des Joachims TS: 448 MW

Current Status (2017):
Holden : 240 MW (Fall)
Des Joachims : 418 MW (S)

SCO N-E-Essa:
- limits M6E/M7E loading
- Load transfers to Barrie TS
Or
Negotiated Generation reduction (IESO/H1/GEN)

Doubles:
B82V + B83V (IESO Recog)
M80B + M81B (H1-only)

Fig. 12 AMPAC/IEEE 738-2006 Hybrid vs. AMPAC Histogram and Contingency Analysis

- The new AMPAC/IEEE 738-2006 hybrid evaluates higher values for continuous ratings approx. 3 to 6 % than AMPAC for most of the lines.
- The new AMPAC/IEEE 738-2006 hybrid evaluates higher values for 15 min ratings approx. 2 to 5 % than AMPAC for most of the lines.
- Contingency Analysis performed in critical HV circuits demonstrate that the hybrid algorithm would have negligible impact on thermal ratings of circuits that have already thermal constraints.

8. CONCLUSIONS AND RECOMMENDATIONS

- Reaffirmed Line rating Parameters are interdependent and have complex relationships.
- Annealing consideration dropped in late 70s that enabled higher maximum conductor temperature limits.
- Weather parameters measured at different locations are difficult to validate, and the geographical terrain dependencies govern the wind speed and angle.
- Retain Hydro One policy of considering Wind Speed as 4 km/h, and Angle as 20°.
- Revisit planning ratings guiding principles to increase ambient temperature (summer) from 35°C to 40°C due to global climate change.
- Pre and post contingency, monitor total number of hours lines are loaded at 75% or over of their continuous rating and have max conductor temp of 93°C.
- Initiate a comprehensive research on Annealing for the usage of max conductor temperatures up to 150°C for continuous rating and considering in particular conductor aging and its life expectancy.
- Conductor snapping incidents should be examined from Annealing standpoint.
- Continue investigating the impact of weather assumptions to improve accuracy of thermal ratings calculations.

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