5L29/5L31

THERMAL PERFORMANCE ASSESSMENT

WINTER RATINGS REPORT

Prepared for: **British Columbia Transmission Corporation**

BC hydro

ENGINEERING

Report No. E497
December 2006

5L29/5L31

THERMAL PERFORMANCE ASSESSMENT

WINTER RATINGS REPORT

ENGINEERING

Report No. E497
December 2006
WPR-2446

5L29/5L31
THERMAL PERFORMANCE ASSESSMENT

WINTER RATINGS REPORT

Prepared by: ______________________
S. Cherukupalli, Ph.D.,, P.Eng.
Specialist Engineer, Task Manager

Reviewed by: T. Kojima
T.Kojima, P.Eng.
Specialist Engineer

Submitted by: R. Nelson
R. Nelson, P.Eng.
Project Manager

BC hydro

ENGINEERING

Report No. E497
December 2006
WPR-2446

ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance of the following personnel during various stages of this project:

Joseph Jue	For sponsoring and providing advice during the course of the project
Takashi Kojima	For providing preliminary assessment of the impact of new ratings on hydraulic pressures
Devinder Ghangass and Mike Kwok	For defining the short-term load profile for short-term rating calculations
Ross Nelson	For advice on the planning and operating ratings from a System perspective

5L29/5L31
THERMAL PERFORMANCE ASSESSMENT

WINTER RATINGS REPORT

CONTENTS

LIST OF FIGURES

Report No. E497
December 2006
WPR-2446

DISCLAIMER

This Report was prepared solely for British Columbia Transmission Corporation. All parties other than BC Hydro are third parties.

BC Hydro does not represent, guarantee or warrant to any third party, either expressly or by implication:

(a) the accuracy, completeness or usefulness of,

(b) the intellectual or other property rights of any person or party in, or

(c) the merchantability, safety or fitness for purpose of,

any information, product or process disclosed, described or recommended in this Report.

BC Hydro does not accept any liability of any kind arising in any way out of the use by a third party of any information, product or process disclosed, described or recommended in this Report, nor does BC Hydro accept any liability arising out of reliance by a third party upon any information, statements or recommendations contained in this Report. Should third parties use or rely on any information, product or process disclosed, described or recommended in this Report, they do so entirely at their own risk.

COPYRIGHT NOTICE

EXECUTIVE SUMMARY

This report discusses the analyses undertaken to determine new Winter steady-state and short-term ratings as well as the assumptions made to arrive at these ratings for the 5L29/31 submarine cables. The rationale of the approach, the assumptions made, and the ratings obtained are discussed.

Two new winter ratings under forced cooled conditions for 5L29/31 submarine transmission cables were developed.

First, a steady-state winter rating of 1535A (1320 MW).

Second, a winter short-term rating of 1664A (1440 MW); based on the BCTC supplied hypothetical load profiles comprising of two, 4 hour peak overload periods over a 5-day period,. Computed transient thermal response demonstrated that the maximum conductor temperature of 85°C is reached using this load condition. The 5-day hypothetical overload scenario must be used cautiously since some winter peaks can last longer than 5-days. It also assumes that the post overload current drops down to the pre-load overload current for at least 240 hours before the next hypothetical load cycle can be applied to the cable. Also this is not a steady-state rating but only a short-term overload rating for the 5L29/31 circuits.

Final hydraulic calculations to quantify the transient hydraulic pressure that can be expected with transient loading at the new ratings have still to be undertaken. This will require clear definitions for the anticipated transient load conditions. Several assumptions were identified in developing the above Winter steady-state and short-term ratings. Based on a careful review of a previous study on hydraulic pressure calculations by the cable manufacturers, our knowledge and experience, the risk of these assumptions and in particular that transient fluid pressures will be exceeded for the new steady state and short-term loadings are judged to be low.

5L29/5L31
THERMAL PERFORMANCE ASSESSMENT

REVISED RATINGS REPORT

1.0 BACKGROUND

BC Hydro's 525 kV ac submarine cable system forms a vital part of the Cheekeye-Dunsmuir transmission system. It comprises two parallel 525 kV circuits, each capable of transmitting 1200 MW (1410A). The implicit assumption is that 50% of the cable charging current for each crossing flows into each cable terminal. An 8 km section crosses Malaspina Strait between Cape Cockburn terminal (CCB) on Nelson Island and Texada East terminal (TXE), while the remaining 30 km section crosses the Georgia Strait between Texada West terminal (TXW) and Nile Creek terminal (NCT) on Vancouver Island, just north of Qualicum.

There are a total of 12 single core, self-contained fluid-filled (SCFF) cables. Each cable manufacturer [Pirelli and STK (Alcatel)] manufactured six lengths each of the required number of cables. Six cables designated M1-M6 cross-Malaspina Strait and six cables designated G1-G6 cross Georgia Strait, with their numeric references extending from North to South. Circuit 5L29 has two Pirelli cables and one STK cable while circuit 5L31 has two STK cables and one Pirelli cable at each crossing. The Pirelli cables use a synthetic fluid and have a smaller fluid duct diameter (25 mm) whereas the STK cables use a mineral fluid and have a larger fluid duct diameter (30 mm).

This report discusses the analyses undertaken to determine new Winter steady-state and short-term ratings as well as the assumptions made to arrive at these ratings. The following section describes the key findings that were considered when developing these revised Winter ratings.

2.0 KEY FINDINGS IN EARLIER STUDIES RELEVANT TO CIRCUIT RATINGS

In order to better understand the impact of the coolant circulation and chiller system have on the conductor temperatures and hence the ampacity rating of the cable, with the cooperation of System Control Centre (SCC), a series of tests were conducted at NCT. The tests comprised of the following steps:

1. Shutdown of the chiller and coolant circulation system for a period of approximately 10-days so that the temperatures could reach steady-state conditions (cognizant that load currents can keep changing and one can exercise little control with this changing condition).
2. Start up of the coolant circulation system and held for a period of 6-days.
3. Start up of the chiller system for a period of 7-days.
4. Shutdown of the chiller system for 6-days.
5. Shutdown of the coolant circulation system for 9-days.
6. Restoration of the coolant circulation system to commence normal operation

The principal conclusions relevant to these studies (thermal assessment), natural and forced cooling, and its impact on winter ratings are discussed in the following section.

- When the circulation is turned OFF (during the test period resulting in natural cooling) the temperatures of the Pirelli cables in circuit 5L29/31 diverge from each other by about 4°C even though the line currents remain the same. The STK cables in these circuits remain the coolest of the three cables.
- Under natural cooling conditions (during the test period), ampacity studies[1] using measured cable and sheath currents demonstrated that the computed and measured conductor temperatures yielded a good match, for an adopted soil thermal resistivity of 0.6°Cm/W
- When the coolant circulation and the chillers were turned ON the conductor temperatures monitored at NCT dropped by about 10-12°C.

---

[1] Using CYME ampacity program

The exact decrease is difficult to estimate as the cable currents were also changing. The corresponding changes in the armour temperatures showed similar trends but there were differences in the absolute temperatures. This suggests that there can be a difficulties in inferring the conductor temperature from the armour temperature and may lead to erroneous conclusions on circuit ratings. This actively demonstrates the benefits of measuring the conductor temperature directly.

- Under forced cooling conditions, a similar study showed some divergence in these temperatures with the program predicting higher temperatures. There were several reasons that can explain the observed discrepancies between the measured and calculated temperatures, such as
    - Anisotropy in the soil thermal resistivity.
    - Assume AC resistance of conductor being different from the cable's intrinsic AC resistance.
    - Possibility of the fluid pumps introducing cold fluid from the tanks into the cable core.
- Generally, the Pirelli cables while carrying lower currents, run hotter than the STK cables.

The following section provides a summary of the new circuit ratings based on some measurements undertaken at NCT station for this circuit.

3.0 REVISED STEADY STATE WINTER RATINGS

The current System Operating Order does not distinguish between winter and summer ratings. As stated in Section 2 of this report, the cable conductor temperature trends down with the observed decrease in soil temperature over the monitored period at constant current. As a first step a circuit loading ability could be easily derived based simply on this knowledge of the ambient soil temperature (@1.5 m depth), and soil thermal resistivity under natural cooled and forced cooled conditions. Using the knowledge gained from these time-limited tests done during late October new Winter ratings were developed.

It is important to note while the calculations to compare measured and computed conductor temperatures used a soil thermal resistivity of 0.6°Cm/W due to the limited period of testing a conservative choice of 0.7°Cm/W has been made in arriving at these new ratings. Table 1 provides a comparative summary of the present and computed prospective steady-state winter ratings for this circuit following the successful deployment of DTS system and the measurements undertaken at NCT over a two-year period.

In arriving at the new ratings the circuit load factor has been assumed to be unity.

Table 1: Comparison between existing steady-state ratings and revised winter ratings based on field measurements at Nile Creek during October - February 2006.

Circuit Names	**Existing ratings**	**Revised Ratings**
	Winter/Summer	Winter
Ratings with shore cooling (Amps)	1410	1535
Ratings with shore cooling (MW)	1200	1320
Ambient soil temperature (°C)	20	12
Soil thermal resistivity (°Cm/W) in Section 4	0.9	0.7
Cable burial depth (m) in section 3	1.5	1.5
Daily Load factor used	1.0	1.0

It is important to note that the 1535 A (1320 MW) stated above comprises of both the load and 50% of the total charging current (994A). So the load current is computed as per equation below:

$$I_{load} = \sqrt{1535^2 - 497^2}$$

$$\mathrm{Re}\,alPower = \sqrt{3} * 525 * 10^3 * I_{load}$$

4.0 EXAMINATION OF CONDUCTOR STEADY STATE TEMPERATURES ALONG ALL CABLE SECTIONS FOR THIS NEW WINTER RATING

When Pirelli and STK (Alcatel) first submitted their ampacity ratings calculations they had identified five distinctly different thermal sections listed below:

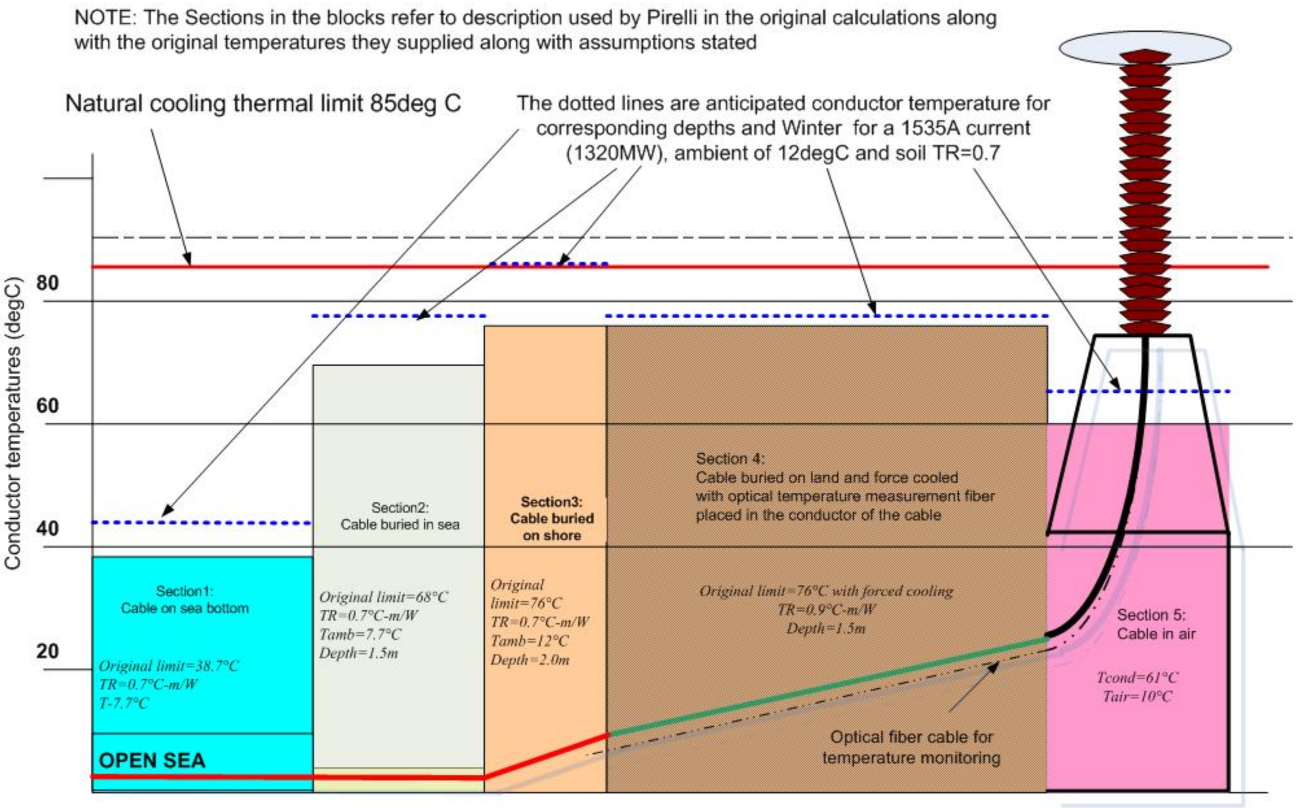
1. Section of the cable in the open sea lying on the sea bottom (Sea temperature at assumed to be 7.7°C).
2. Cable buried in sea bottom (sea temperature 7,7°C, soil thermal resistivity (Tr=0.7°C-m/W)
3. Cable buried on shore (soil temperature 12°C, soil thermal resistivity (Tr=0.7°C-m/W, with a cable buried at a depth 2.0 m).
4. Cable buried on land (soil temperature 20°C in summer, soil thermal resistivity (Tr=0.9°C-m/W, with a cable buried at a depth 1.5 m).and subjected to forced cooling.
5. Cable in air with no armour and terminated in pothead (air temperature 10°C).

As per the manufacturer’s original calculations Figure 1 shows the maximum conductor temperature reached by the cable in each of these sections for the stated ambient temperatures and soil thermal resistivities for a circuit load of 1410A0 (1200 MW). From these analyses, Section 4 was deemed to be the thermally governing section. For section 4, based on data acquired to-date and the analyses performed, a soil Tr=0.7°Cm/W and a winter ambient soil temperature at depth of 1.5 m to be 12°C seemed more appropriate under forced cooling conditions. These changes will yield lower conductor temperatures for the same current.

The new winter rating was calculated to be 1535 A (1320 MW) which corresponds to an 85°C conductor temperature in Section 3. The corresponding temperatures reached by the remaining sections are also shown in Figure 1 as dotted lines. Clearly, if the maximum conductor temperature of 85°C is imposed Section 3 now “becomes” the thermally limiting section for the assumed conditions of soil thermal resistivity and soil temperatures in Section 3. This section is the region just past the forced cooling section where the cable is covered with native soils for about 20m out into the ocean. It has also been assumed that the soil temperature is 12°C. This section is generally wet/moist and is likely to have lower thermal resistivity and soil temperatures than those displayed and used in the calculations. Until further monitoring and data analyses is performed to confirm that they are indeed lower than assumed it will be prudent to continue to use the stated values of soil temperature and soil thermal resistivity.

It is important to bear in mind, that the thermal conditions at TXW and TXE remain unknown. Very limited current measurements at TXW indicated that under the prevailing circuit loading the currents at NCT were the highest. This suggested that the cable landing site at NCT appeared to be the thermally governing section. As an interim, based on the available data, it seems possible to use some form of ambient adjusted ratings that will be useful as guide for the upcoming Winter peak.

During the Tendering stage of the original project it was pointed out that the governing section was the one from the 20-40 m to 100 m water depth where one of the cable suppliers advised the conductor temperature rise should be limited to 60°C. The reason for limiting the temperature rise in this section is the uncontrolled embedding conditions which may cause uncontrolled thermo-mechanical stresses with possible reduction of the fatigue life of the lead sheath. This limit was subsequently waived.



NOTE: The Sections in the blocks refer to description used by Pirelli in the original calculations along with the original temperatures they supplied along with assumptions stated

Natural cooling thermal limit 85deg C

The dotted lines are anticipated conductor temperature for corresponding depths and Winter for a 1535A current (1320MW), ambient of 12degC and soil TR=0.7

5L29/31 525 kV Pirelli submarine cable conductor temperature at various sections approaching NILE CREEK at the original current rating of 1410A (1200MW) in winter and corresponding predicted temperatures with the revised Winter ratings (1535A ~1320MW))

Figure 1: Five different cable sections that show the original Pirelli computed conductor temperatures for a 1410A (1200 MW) ratings and the anticipated conductor temperatures for the revised Winter ratings of 1535A (1320 MW)

This potential for higher power transfer (ratings), are based on the following assumptions:

- The measured cable currents are the highest at NCT station making it the thermally governing section.
- The cables transient fluid pressure constraints are within the design limits.
- The ability of the other series equipment in the line such as transformers, connecters, CTs, bus work are within power transfer limits being recommended.
- The cable fluid pressurizing and forced cooling system remain reliable.
- Cable dissipation factor has remained unchanged from factory QA tests.
- The soil thermal resistivities at all four sites (NCT, CCB, TXW, and TXE) exhibit similar behaviour when extrapolated to higher than tested load currents.

Based on our knowledge and experience, the risks of the above stated assumptions and in particular, that transient hydraulic pressures shall be exceeded for the newly stated ratings, are low.

In addition, the following system parameters are considered to be conservative:

- Application of the 85°C limit
- Unity daily load factor
- Soil thermal resistivity of 0.7°C-m/W and soil temperature of 12°C in winter for Section-3

The merits of re-examining these parameters and their implications on ratings have to be carefully reviewed.

5.0 SHORT-TERM CIRCUIT RATINGS

In 1995, BC Hydro Planning department wanted a transient study undertaken to calculate a 5-day short-term overload rating. The short-term ratings were defined to be 10 minutes; 2 hour and a 5-day heavy duty loading. The hypothetical overload period for this cable system along with the pre-loading conditions were also defined. This 5-day load shape was derived from historical data of four winters from 1990/1991 to 1993/1994 with daily morning and afternoon peaks. The 5-day short term loading as per a hypothetical loading pattern was defined as shown in Figure 2a. The transient thermal response for this anticipated service condition was supplied to System Control and System Planning. These results demonstrated that the allowable ratings under these conditions were determined to be 1550A (1335 MW).

Based on discussions with BCTC and more recent studies this hypothetical curve was altered to increase the maximum overload period from 2 hours to 4 hour per day with a pre-load current of 1330A (1120 MW). This study was intended only for planning purposes and not for system operation. Using this newly defined hypothetical load pattern computations were undertaken for the cable section buried on shore under winter conditions (illustrated in Figure 1). The analyses showed that the new allowable maximum overload current was 1660A (1440 MW). The temperature response results shown in Figure 3 demonstrates that the maximum conductor temperature of 85°C is reached when the cable is subjected to this hypothetical load pattern with a maximum current of 1660A and a pre-load current of 1330A.

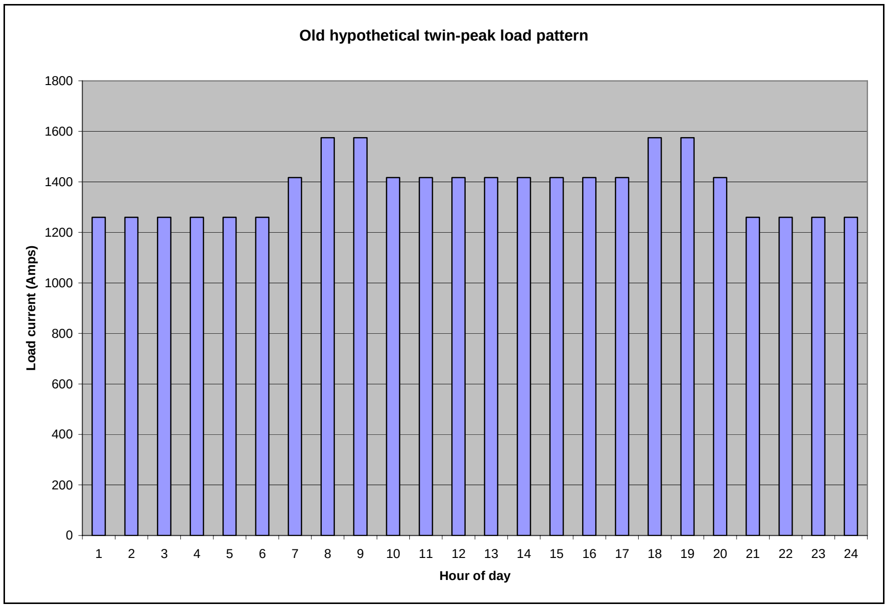


Figure 2a: Hypothetical load pattern as per the 1995 study.

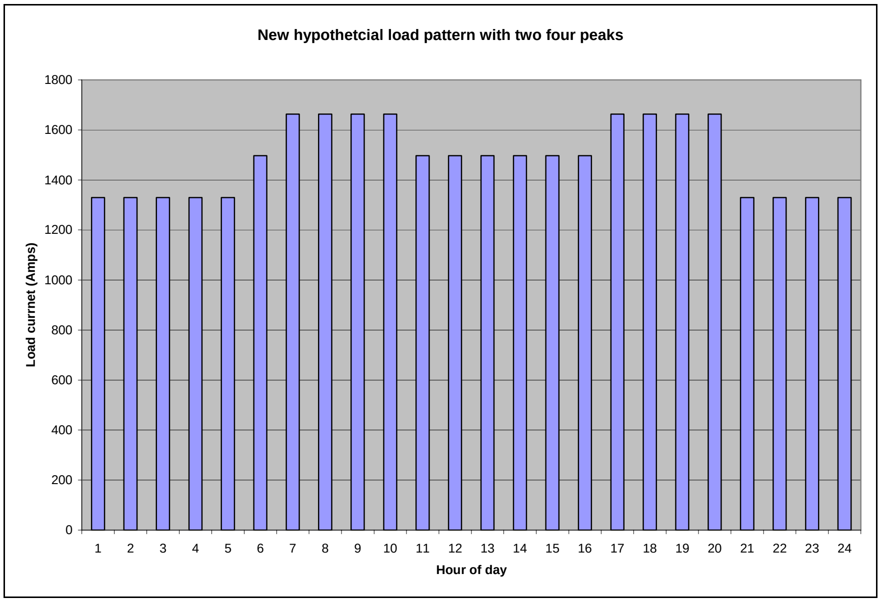


Figure 2b: Amended load pattern provided by BCTC for a pre-load current of 1330A with the maximum current being carried by the cable over a four hour period once in the morning and once in the evening.

6.0 DISCUSSIONS

SCFF cables are subjected to both static and transient hydraulic pressures and must be operated within an allowable limit. While the static hydraulic pressure in this system is maintained within a pre-set range, a transient fluid pressure can be imposed on the cable as a result of sudden change in circuit loading conditions (either load increase or load rejection). The transient pressures will be a function of the following parameters:

- Cable length
- Fluid channel diameter
- Rate of change of the temperature of the fluid in the cable. This in turn depends on the pre-current, short-term overload currents, and ambient temperature.

Generally, a higher rate of temperature change would result in a higher transient fluid pressure.

In December 1998 transient hydraulic pressure calculations were performed by Pirelli and STK for different types of circuit loading for various set of loading patterns and load rejection conditions. The present hypothetical load pattern does not correspond to any of the ones used in this study. So, a separate hydraulic transient pressure computation has to be undertaken to confirm that the proposed steady-state and short-term overload ratings computed does not pose a problem for cable operation. Based on our knowledge and experience, however, the risk of the transient pressures being exceeded under the revised operating conditions is judged to be low. Correspondence has been initiated with manufacturer(s) to quantify the transient pressures for the proposed short-term winter ratings that are being introduced. This work is yet incomplete.

The 5-day hypothetical overload scenario must be used cautiously since some winter peaks can last longer than 5-days. Further, this is not a steady-state rating but only a short-term overload rating. It also assumes that the post overload current drops down to the pre-load overload current for at least 240 hours before the next hypothetical load cycle can be applied to the cable.

It is important to recognize that with the ability to measure the conductor temperatures in the forced cooling section (Section 4) at NCT and CCB can help verify these calculations. Also if additional measurements of the seasonal sea-water temperatures and soil thermal resistivities are measured in the transition sections (Section 3 and 4) it will aid in refining the models, and improve the understanding of the pre-load/overload relationships.

7.0 CONCLUSIONS

Two new winter ratings under forced cooled conditions for 5L29/31 submarine transmission cables were developed.

First, a steady-state winter rating of 1535A (1320 MW).

Second, a winter short-term rating of 1664A (1440 MW); based on the BCTC supplied hypothetical load profiles comprising of two, 4 hour peak overload periods over a 5-day period. Computed transient thermal response demonstrated that the maximum conductor temperature of 85°C is reached using this load condition. The 5-day hypothetical overload scenario must be used cautiously since some winter peaks can last longer than 5-days. It also assumes that the post overload current drops down to the pre-load overload current for at least 240 hours before the next hypothetical load cycle can be applied to the cable. Also this is not a steady-state rating but only a short-term overload rating for the 5L29/31 circuits.

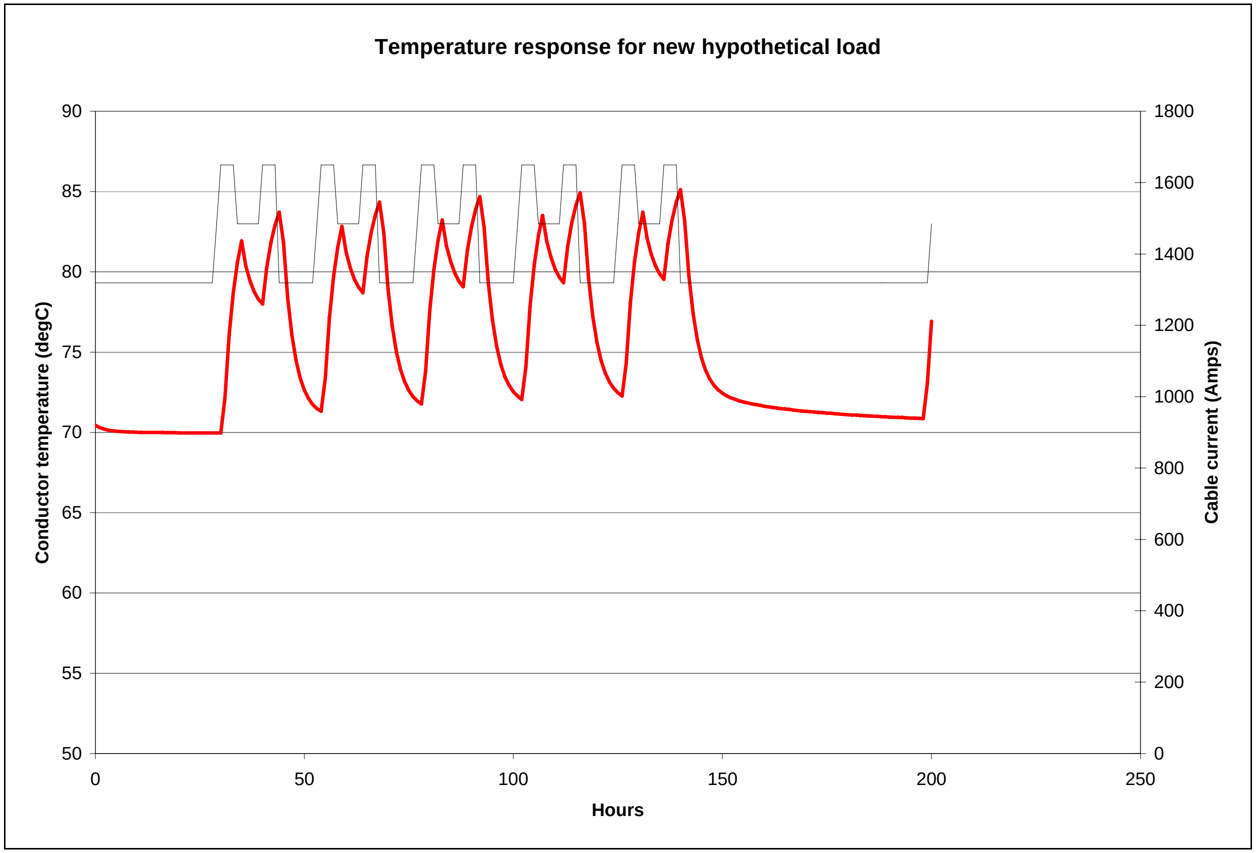


Figure 3: Computed transient response for a twin peak loading pattern over a 5-day period with an initial current of 1330A that increase by 25% (1662A-1440 MW) over normal steady state loading during the peak period. Clearly, the conductor temperatures are below the 85° temperature limit for the winter ambient of 12°C and soil thermal resistivity of 0.7°Cm/W.

Final hydraulic calculations to quantify the transient hydraulic pressure that can be expected with transient loading at the new ratings have still to be undertaken. Several assumptions were identified in arriving at the above Winter steady-state and short-term ratings. Based on our knowledge and experience, the risk of these assumptions and in particular that, transient fluid pressures will be exceeded for the new steady state and short-term loadings are judged to be low.

In addition, the following system parameters are considered to be conservative:

- Application of the 85°C limit
- Unity daily load factor
- Soil thermal resistivity in Sections 3-4
- Assumed ambient soil temperatures of Sections 3 and 4.