POWER LINES PRO SOFTWARE

VERIFICATION OF CALCULATED RESULTS

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1. Background

The creators of *Power Lines Pro* engaged Electro Technical Consultants P/L to perform an independent verification of the results yielded by their software package.

A number of sample results produced by *Power Lines Pro* (*PLP*) have been checked by comparison with:

- hand calculations
- results produced by other well-established line design software packages.

This verification is based on a number of samples and test cases; it does not claim to be an exhaustive check of the results produced by *Power Lines Pro* for every possible line configuration, conductor and load case.

The calculation methods used in this analysis are in accordance with *AS/NZS 7000:2010* 'Overhead line design—Detailed procedures' and assume a rigid pole with no movement below ground line.

The conductor library supplied with the software used values taken from the Olex Cables catalogue. It should be noted that there may be slight discrepancies between these values and those listed within the respective Australian Standards for conductors, values used by various electricity supply authorities or other line design software. Some parameters, e.g. Modulus of Elasticity, were modified in the following test cases to facilitate comparison with other software packages.

2. Sag/Tension and Blowout Calculations

For the following calculations, it is assumed that:

- conductors have been pre-stressed or overtensioned initially so that the effects of creep (inelastic stretch or permanent elongation) may be ignored
- no span reduction factor is applied
- conductor stretch is allowed for under blowout conditions.

Hand calculations for this section are contained in Appendix 2.

The table below shows some of the tools/methods used to calculate results in the cases that follow.

Code	Tool/Method	Remarks
PLP	Power Lines Pro	
H	Hand Calculation	
PnW	Poles'n'Wires	Powermation software, v. 5.0
MD	MainsDes	Energex software
PLS	PLS-CADD	Power Line Systems Inc software
S10	Sag10	Southwire Inc. software

Various combinations of conductor, span length, stringing tension, wind pressure and temperature are considered in the table below and the results yielded by various calculation tools compared.

String Temp (°C)	String Tension (%CBL)	Conductor	Span Length (m)		Ruling Span (m)	Cond Temp (°C)	Cond Wind Press (Pa)	Calc Tool	Sag (m)	Tension (kN)	Blowout (m)
			Hor	Vert							
15	18	Krypton AAAC 1120 19/3.25 (56MPa MoE used in this case.)	120	0	120	15	0	**PLP**	**1.14**	**6.73**	
								H	1.14	6.73	
								PnW	1.14	6.73	
								Sag10	1.14	6.73	
								PLS	1.16	6.73	
						15	500	**PLP**		**9.54**	
								H		9.54	
								PnW		9.54	
								Sag10		9.55	
								PLS		9.51	
						30	500	**PLP**		**8.21**	1.79<62°
								H			<62°
								PnW		8.21	1.78
						0	0	**PLP**	**0.86**	**8.88**	
								PnW	0.86	8.88	
						75	0	**PLP**	**2.54**	**3.01**	
								H	2.54	3.01	
								PnW	2.54	3.01	
								Sag10	2.55	3.02	
								PLS	2.56	3.04	
			120	0	103.92	75	0	**PLP**	**2.82**	**2.71**	
								H	2.82	2.71	
								PnW	2.82	2.71	
15	10	7/2.00 HDC	100	0	100	75	0	**PLP**	**3.33**	**0.73**	
								PnW	3.34	0.72	
15	10	Moon AAC 7/4.75 (59MPa MoE used in this case.)	100	0	100	15	0	**PLP**	**2.21**	**1.88**	
								PnW	2.22	1.88	
								MD	2.22	1.88	
						75	0	**PLP**	**3.13**	**1.33**	
								PnW	3.14	1.33	
								MD	3.13	1.33	
						75	500	**PLP**		**3.02**	**2.96<65°**
								PnW		3.02	2.97
								MD		3.02	2.96<65°
			100	30	100 / 95.8[1]	15	0	**PLP**	**2.35**		
								PnW	2.32		
						75	0	**PLP**	**3.37**		
								PnW	3.28		

The sag/tension and blowout results yielded by *Power Lines Pro* are consistent with hand calculations and results produced by other software packages. The slight differences in results above are due to small differences in conductor parameters used, rounding error (not necessarily on the part of *PLP*) or slight differences in calculation method, e.g. *PLS-CADD* uses finite element analysis.

[1] The ruling span value of 95.8m is correctly calculated by *Power Lines Pro* in accordance with the formula for inclined spans given in Appendix S section 5 of *AS/NZS 7000:2010*.

3. Pole Tip Load and Stay Load Calculations

For simplicity, we will use load factors of 1.0 throughout. Also, it is assumed that conductor wind pressure is proportional to the sine of the angle of the wind to the conductor i.e. maximum effect when the wind is perpendicular to the conductor, but falling off in other directions.

3.1 Simple Termination Pole

Consider the case of an 11m 8kN WS Ausgrid pole on which a single conductor of MOON conductor (again with 59MPa MoE) from the east terminates at the tip. Key parameters are as follows:

Conductor stringing tension: 10%CBL at 15°C
Modulus of elasticity of conductor: 59MPa
Sinking depth of pole: 2.14m
Tip height of pole: 8.86m
Groundline diameter of pole: 331mm
Tip diameter of pole: 260mm
Temperature at which tip loads are calculated: 15°C
Conductor wind pressure (when perpendicular): 900Pa
Pole wind pressure: 1300Pa

The tip loads calculated by *Power Lines Pro* are as follows:

No wind: 1.88kN (all due to conductor tension)
Max. wind: 6.79kN <109.9°for worst-case wind direction of 351°, comprising"
6.12kN <90.0° conductor longitudinal
0.63kN <180.0° conductor transverse
1.70kN <171.0° pole windage

These results may be checked by hand calculation, as follows:

No-wind tip load = conductor tension = 10% x 18.8kN = 1.88kN (Agrees!)

Above-ground projected area of the pole = (0.331 + 0.260)/2 x 8.86 = 2.62m^2
Tip load due to pole windage = 1.300 x 2.62 x 0.5 = 1.70kN

For a wind angle of 351°, the wind is 81° off the direction of the conductor.
Effective conductor wind pressure = 0.900 x sin 81° = 889Pa
Longitudinal conductor tension under 889Pa wind = 6.16kN
Transverse conductor load on 50m wind span = 50 x 0.01425 x 0.889 = 0.63kN

Vector sum of cond. longitudinal, cond. transverse, pole windage = 6.83<109.8° (Agrees!)

For comparison purposes, *Poles'n'Wires* yields the following results:

No wind: 1.88kN
Max. wind: 6.88kN <71°/109° for worst-case wind direction of 194°/346° (Similar to PLP!)

It was found that *Power Lines Pro* correctly reduces tip load attributable to conductor action as conductors are lowered in proportion to their height of attachment relative to tip height.

3.2 Simple Intermediate Pole with Nil Deviation Angle

Consider the pole from section 3.1 above, but this time with the conductor passing through from east to west with nil deviation at the pole.

The tip loads calculated by *Power Lines Pro* are as follows:

> No wind: 0.0kN
> Max. wind: 2.99kN <180.0°for worst-case wind direction of 0°

For comparison purposes, *Poles'n'Wires* yields the following results:

> No wind: 0.0kN
> Max. wind: 2.99kN <0°/180° for worst-case wind direction of 180°/0° (Agrees!)

The two conductor spans have cancelling longitudinal tension, of course. In nil wind conditions, the tip load is, therefore, nil. Under wind conditions, the conductor transverse load is 2 x 0.63kN = 1.26kN, which adds to the pole wind load contribution of 1.70kN to give a total load of 2.96kN. (Agrees!)

3.3 Simple Intermediate Pole with 20° Deviation Angle

Consider the pole from section 3.2 above, but now with a 20° deviation in line direction at the pole.

The tip loads calculated by *Power Lines Pro* are as follows:

> No wind: 0.65kN (all due to conductor tension)
> Max. wind: 5.05kN <10°for worst-case wind direction of 190°

For comparison purposes, *Poles'n'Wires* yields the following results:

> No wind: 0.65kN (Agrees!)
> Max. wind: 5.09kN <10° for worst-case wind direction of 190° (Similar to *PLP*!)

Checking by hand calculation, for the nil wind case the tip load will be vector sum of 1.88N<90° and 1.88kN<290° = 0.65kN<10°. (Agrees!)

For the wind case, we have an effective wind pressure on the conductors of 900 x sin 80° = 886Pa, which equates to a conductor tension of 6.14kN (acting in directions of 90° and 10°). The transverse load applied by each conductor span will be 0.63 sin 80° = 0.62kN (acting at 0° and 20°). The wind load on the pole will be 1.70kN <10°. Adding these vectorially, we obtain a result of 5.05kN <10° (Agrees!)

3.4 Simple Termination Pole with Opposing Stay

Consider the pole from section 3.1 above, but with a stay installed opposite the conductor, attached at the top of the pole with a ground angle of 45°.

The tip loads calculated by _*Power Lines Pro*_ are as follows:

> No wind: 0.0kN (all due to conductor tension)
> Max. wind: 2.35kN <180.0°for worst-case wind direction of 0°

For comparison purposes, _*Poles'n'Wires*_ yields the following results:

> No wind: 0.0kN
> Max. wind: 2.35kN <0°/180° for worst-case wind direction of 180°/0° (Agrees!)

*Power Lines Pro* calculates the load in the stay wire as follows:

> No wind: 2.66kN
> Max. wind: 9.03kN for worst-case wind direction of 350°, countering a tip load of 6.39kN

Hand calculation for no wind conditions involves dividing the conductor tension, 1.88kN, by the cosine of 45°, yielding a result of 2.66kN. (Agrees!)

Under wind conditions, though, the calculation is more complicated. The worst case stay loading occurs, not when the wind is perpendicular to the pole, but when it is 10° off perpendicular such that there is some wind action on the pole as well as on the conductor. The pole load will be 1.70kN x sin 10° = 0.295kN. The effective wind pressure on the conductor will be 900 x sin 80° = 886Pa, giving a longitudinal tension of 6.14kN. This equates to a tip load of 6.43kN. The stay load will be 6.43kN divided by cos 45°, i.e. 9.09kN. (Similar to *PLP*!)

It was also found that *Power Lines Pro* correctly increases stay wire loading as:

- the angle of the stay to the ground increases
- the stay wire attachment point is lowered on the pole.

3.5 Simple Termination Pole with Stay Offset

Consider the pole from section 3.4 above, but this time with a stay installed in a direction 20° off the ideal direction opposite the conductor.

The tip loads calculated by _*Power Lines Pro*_ are as follows:

> No wind: 0.64kN (all due to conductor tension)
> Max. wind: 4.36kN <20°for worst-case wind direction of 185°

For comparison purposes, _*Poles'n'Wires*_ yields the following results:

> No wind: 0.64kN
> Max. wind: 4.38kN <20° for worst-case wind direction of 185° (Agrees!)

3.6 Tee-off Pole

Consider the pole from section 3.2 above, i.e. an in-line pole, but this time with a tee-off at 90°, again a single conductor of Moon @ 10%CBL on a 100m span attached at the tip of the pole.

The tip loads calculated by *Power Lines Pro* are as follows:

No wind: 1.88kN
Max. wind: 6.83kN <160.5°

For comparison purposes, *Poles'n'Wires* yields the following results:

No wind: 1.88kN
Max. wind: 6.88kN <161° (Similar to *PLP*!)

4. Profiling and Conductor Clearances

Power Lines Pro was used to model a 100m span of Moon conductor (again with 59MPa MoE) strung at 10%CBL between two Ausgrid 6/11 poles with 2.14m embedment. The conductor was attached at the pole tips, i.e. at a height of 8.86m.

The midspan sag in the conductor was 2.21m at 15°C and 3.13m at 75°C.

Ground clearance of the 75°C conductor midspan according to the *PLP* Measuring Tool was 5.73m, which is the correct result obtained from subtracting the sag of 3.13m from the attachment height of 8.86m.

When a midspan dip of 3m was created in the groundline under the span, the *PLP* tool correctly indicated a ground clearance of 8.73m.

A second circuit identical to the first was strung 2.0m below the original, i.e. with an attachment height of 6.86m on the two poles. The intercircuit clearance between a hot circuit above and a cool circuit (15°C) below was correctly indicated to be 1.08m (2.0m separation + 2.21m bottom sag – 3.31m top sag).

5. Uplift on Intermediate Poles

Power Lines Pro was used to model two 100m long spans of Moon conductor (again with 59MPa MoE) strung tightly at 20%CBL with the conductor attached at the pole tips. The centre intermediate pole was made relatively short—9.5m embedded 1.89m. When the outer poles were 14m embedded 2.25m, uplift was present on the centre pole (for a temperature of 5°C). The conductor catenary curve clearly rose either side of the centre pole. However, when the outer poles were 11m or 12.5m, no uplift was present on the centre pole.

For comparison purposes, *Poles'n'Wires* yielded similar results: uplift present for 14m outer poles but not for 12.5m outer poles.

6. Conclusion

The results yielded by *Power Lines Pro* for the range of test cases considered herein were correct and consistent with results yielded by hand calculation and other well-established line design software packages. These results pertained to the calculation of:

- conductor sag
- conductor tension
- conductor blowout and blowout angle
- pole tip loads
- stay tensions
- conductor-ground clearances
- conductor-conductor clearances
- presence of uplift on intermediate poles.

When correctly configured, *Power Lines Pro* is able to perform calculations in accordance with the formulas and methods set out in *AS/NZS7000:2010* 'Overhead line design—Detailed procedures'.

Note: While this study has addressed a range of test cases to verify correct functionality of the software generally, it has not included exhaustive testing of all line configurations, conductor types and load cases or testing of all aspects of the software's functionality.

Appendix 1 BRIEF CV OF AUTHOR

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Education

- Bachelor Engineering, Electrical, UQ, First Class Honours, 1981
- Diploma Training and Assessment, 2003
- Diploma Frontline Management, 2003
- Numerous short courses in Electric Power Engineering

Professional Achievements

- Author of 14-module training course in electricity distribution and lighting design used by various electricity supply authorities
- Original developer of widely-used software packages *Poles'n'Wires* and *LVDROP* (though no longer associated with these products)
- Author of a number of overhead line design, construction and maintenance manuals for various electricity supply authorities
- Published papers: "A Statistical Method for Analysing LV Distribution Networks" (1990), "The Economics of Insulated HV Aerial Power Lines" (1995)
- Development of 132kV overhead cross-country structure set (steel monopole and tower) and planning for 150km line through remote locations.

Professional Associations

- Institution of Engineers, Australia, Reg. No. 64052
- C.P. Eng, NPER-3 Electrical College Member No. 297078
- Registered Professional Engineer Queensland No. 3179

Professional Experience

Kent commenced his professional career as an engineer with the South East Queensland Electricity Board in 1981, where he worked in various positions including Regional Design Engineer and Major Consumers Engineer (Brisbane CBD). During 1992 and 1993 he worked as a computer programmer/analyst in the UK, then returned to Australia to manage an electrical manufacturing business, and began developing an engineering consultancy arm. In 1998, Kent created a separate business entity, Electro Technical Consultants P/L. The firm is a medium-sized business providing services to developers and electricity supply utilities in network planning, design (transmission, distribution, substations, road lighting, subdivisions), technical studies and technical training. The firm has produced thousands of designs for electricity network extensions and upgrades.

The author is entirely independent of the developers of *Power Lines Pro* and currently has no commercial interest in any line design software on the market.

Appendix 2 HAND CALCULATIONS FOR SAG/TENSION

For simplicity, hand calculations have used formulae based upon modelling the shape of the catenary as parabolic, which is accurate to within 1% for spans with a sag/span ratio of 0.1 or less.

The basic parabolic equation relating sag and temperature is as follows:

$$D = \frac{wL^2}{8T}$$

For a Krypton tensioned to 18% CBL, the sag *D* in a 120m span is calculated as follows:

$$T_1 = 0.18 * 37400 = 6732N$$
$$D_1 = \frac{wL^2}{8T_1} = \frac{0.433kg/m * 9.81m/s^2 * 120^2}{8 * 6732} = 1.14m$$

Calculations for wind and various conductor temperatures are based on the following equations:

$$T_2^2\left[T_2 + K_2(t_2 - t_1) + \left(\frac{K_1 w_1 L}{T_1}\right)^2 - T_1\right] = \left(K_1 w_2 L\right)^2$$
$$K_1 = \sqrt{\frac{EA}{24}} \text{ and } K_2 = \alpha EA$$

Where

L	= length of span (m)		
A	= cross sectional area of conductor (mm²)		
E	= modulus of Elasticity (MPa)		
α	= coefficient of linear expansion (1/°C)		
t_1	= initial temperature (°C)	t_2	= final temperature (°C)
w_1	= initial weight/load (N/m)	w_2	= final weight/load (N/m)
T_1	= initial tension (N)	T_2	= final tension (N)

The above equation is solved in the form T_2^2 (T_2+D) = B by trial and error.

The calculation for a 120m span of Krypton conductor (assuming a 56MPa modulus of elasticity), 15°C and a 500Pa wind perpendicular to the conductor is shown below:

$$K_1 = \sqrt{\frac{EA}{24}} = \sqrt{\frac{56000*157.6}{24}} = 606.4$$
$$K_2 = \alpha EA = 0.0000023*56000*157.6 = 203.0$$
$$w_2 = \sqrt{w_D{}^2 + w_W{}^2} = \sqrt{(0.433*9.81)^2 + (500*0.0163)^2} = 9.19N/m$$
$$D = 203.0*(15-15) + \left(\frac{606.4*4.24*120}{6732}\right)^2 - 6732 = -4624$$
$$B = \left(606.4*9.19*120\right)^2 = 447x10^9$$
$$T_2^2\left[T_2 + D\right] = B$$

Trial and error follows:

T_2	LHS	Difference	Error%
6,732	95545293315	-3.51731E+11	-78.6%
8,000	2.1608E+11	-2.31197E+11	-51.7%
9,000	3.54476E+11	-92800496188	-20.7%
9,540	4.47435E+11	158982467.4	0.0%

The final tension is 9.54 kN.

Now, for no wind and a 75°C conductor temperature, we have:

$$w_2 = \sqrt{w_D{}^2 + w_W{}^2} = \sqrt{(0.433*9.81)^2} = 4.24N/m$$

$$D = 203.0*(75-15) + \left(\frac{606.4*4.24*120}{6732}\right)^2 - 6732 = 7556$$

$$B = (606.4*4.24*120)^2 = 95.5x10^9$$

$$T_2^2\left[T_2 + D\right] = B$$

Trial and error!

T_2	LHS	Difference	Error%
6,732	6.4751E+11	5.51965E+11	577.7%
5,000	3.13889E+11	2.18344E+11	228.5%
4,000	1.84889E+11	89343875026	93.5%
3,008	95579884766	34591450.35	0.0%

The final tension is 3.01 kN with a midspan sag of 2.54m.

Now to check blowout angle for the span at 30°C and a 500Pa wind as follows:

$$\phi_c = \tan^{-1}\left(\frac{500*0.0163}{0.433*9.81}\right) = 62\deg$$

To check Ruling Span calculations, the following formula is used for level spans:

$$RS = \sqrt{(\sum L_i^3 / \sum L_i)}$$

For a strain section with one 120m span and one 60m span, the ruling span is:

$$RS = \sqrt{((120^3 + 60^3)/(120 + 60))} = 103.92m$$

For the above strain section at 75°C conductor temperature, the terms in our tension equation are as follows:

$$K_1 = \sqrt{\frac{EA}{24}} = \sqrt{\frac{56000*157.6}{24}} = 606.4$$

$$K_2 = \alpha EA = 0.0000023*56000*157.6 = 203.0$$

$$w_2 = \sqrt{w_D{}^2 + w_W{}^2} = \sqrt{(0.433*9.81)^2} = 4.24N/m$$

$$D = 203.0 * (75 - 15) + \left(\frac{606.4 * 4.24 * 103.92}{6732} \right)^2 - 6732 = 6951$$

$$B = (606.4 * 4.24 * 103.92)^2 = 7.14x10^{10}$$

By trial and error, for a T_2 value of 2710, $T_2^2 [T_2 + D] = B$

$$D_1 = \frac{wL^2}{8T_1} = \frac{0.433\,kg/m * 9.81\,m/s^2 * 120^2}{8 * 2710} = 2.82m$$