De-rating for Duty Cycle

It is very common for engineers to need to use equipment outside of its stated ratings. The question then arises as to how far one can go before the equipment is going to become damaged or malfunction. Even graduate electrical/electronic engineers can be very unprepared for such real world uncertainty. This is how I think about such problems.

There was a question posed on the Eng Tips forum in December 2014 which is a good example of the problem and I thought it was a good example to explore the more general solution.

The post refers to a Badland Winches model 61840. It has a rated line pull of 2500 lb and the original poster wanted to know what duty cycle he could run it at for a load of 250 lb. Well the data sheet only gives a duty cycle rating of 5% at max rated load, which it further states is 45 seconds at full load and then 14 minutes 15 seconds of rest. We can therefore be confident that the winch can be run at a 250 lb load for 45s, but after that we don't know much, yet. The obvious thing to do is phone (or preferably email) the manufacturer and ask the question. The reason why email is better is that you can at least show your boss that you had an expert opinion to back you up when you burned out the equipment!

Let's suppose that technical support is not forthcoming. Now what?

In this case we have 4 data points for load current on the winch.

First Layer of Wire Rope Performance					
	Line Pull lb. (kg.)		**Line Speed** fpm (mpm)		**Amp Draw** (@ 12V)
1	0	(0)	13.3	(4.1)	10
	1000	(454)	8.3	(2.5)	55
	2000	(907)	4.1	(1.2)	106
	2500	(1134)	2.7	(0.8)	132

but it doesn't have anything for a 250 lb load. Get real! Nobody is likely to have data for the exact operating condition that you want to use.

So plot the data in Excel, curve fit it, and interpolate the value.

That's very neat. We have gone from 132A to 20A with our reduced load. The voltage is fixed so the power has dropped by a factor of $\frac{132}{20} = 6.6$. So does that mean I can run it for 6.6× longer before it burns out or gets to a limiting operating condition? This would mean I could run it for 45s × 6.6 = 297s. The problem is that there has been little consideration of the problem yet. One has to have some sort of mental or simulation model to work with to really understand what one is doing. This can be difficult because thermal modelling is often skimped on engineering courses because it is either too easy or in other cases impossibly hard.

In order to get a good grip on this problem, and others like it, I am going to make a whole bunch of assumptions in order to get something to work with. I am then going to tweak about with these assumptions and see how the solution changes as a result. This tells me if I have robust solution or just a crazy bunch of guesses.

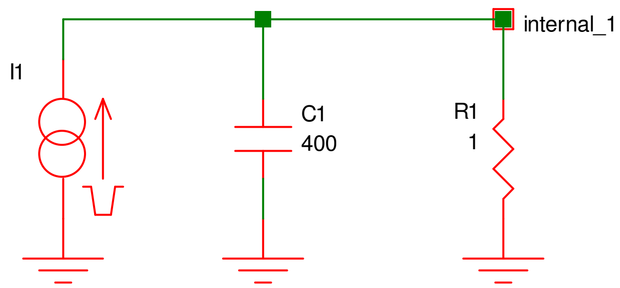
The first thing to know about motors, transformers, and the like, is that they contain copper wire. This wire has an insulation which is going to be unhappy above a temperature of either 120°C for standard wire or 180°C for higher temperature wire.

Now I don't like solving differential equations, and frankly because circuit simulators are freely available, I can't see why I should bother. So therefore I am going to solve an equivalent electrical circuit – I know how to do that.

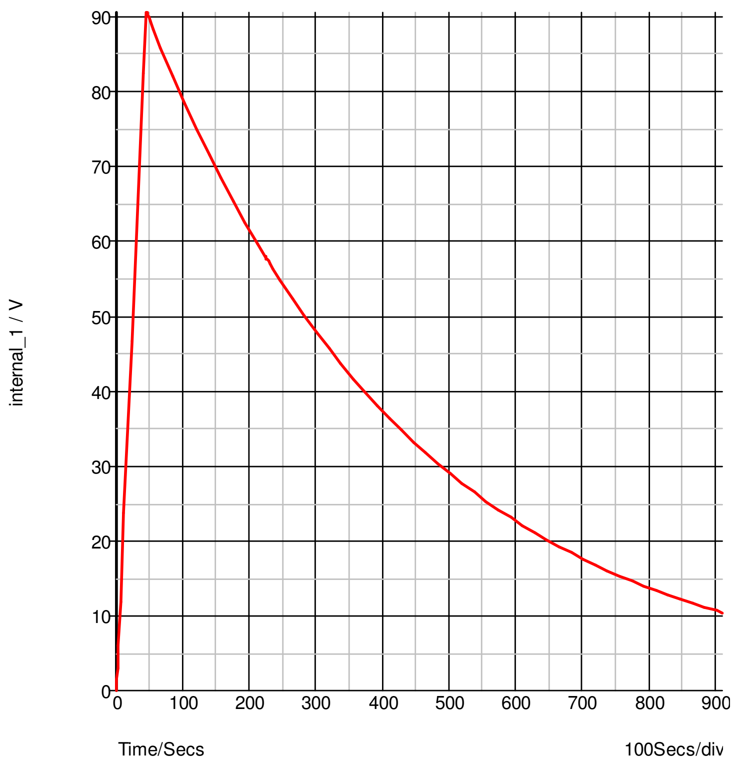
electrical model		**thermal model**	
current	Amps	power	Watts
resistance	Ohms	thermal resistance	°C/W
voltage	Volts	temperature	°C

As a quick "sanity check" if I put current through a resistor I get a voltage. If I put power through a thermal resistance I get a temperature (difference).

So here is my model for the winch.

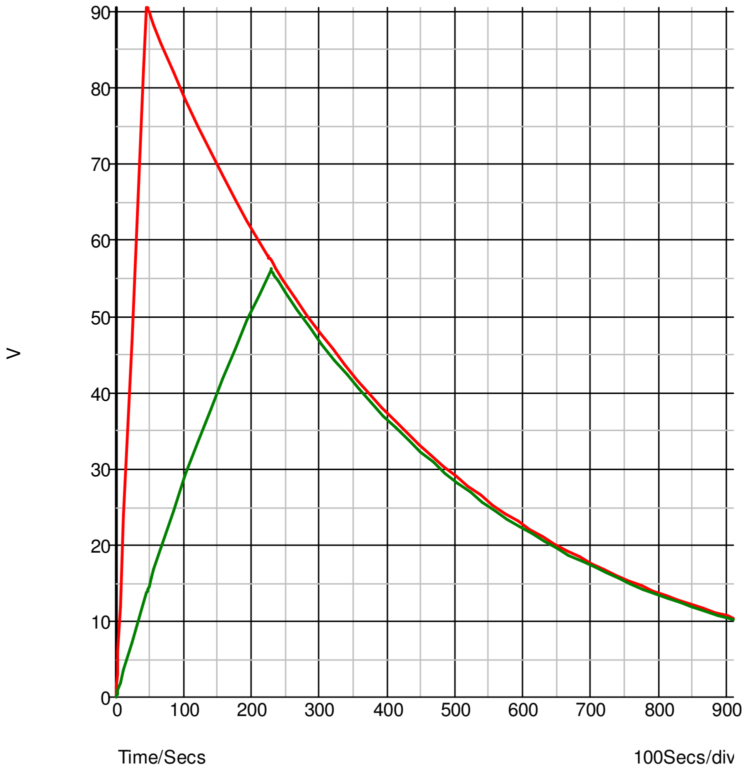


It is not the absolute values of the model which are important. I am mostly interested in the time constant. What I have done is adjusted the values to get the sort of curve I am after.



That sounds a bit vague so let me spell it out. This curve is intended to represent the full power situation. The current source applies current at a fixed value for 45s then shuts off. 900s is of course 15 minutes. What I wanted was a 90°C temperature rise followed by cooling back to 10°C. Why? Well suppose the winch is in a 20°C ambient. If it heats up by 90°C (above ambient) on the first attempt and then cools to 10°C (above ambient) it will hit 100°C on the next cycle. Ok, on subsequent cycles it will be slightly above 10°C, but not much.

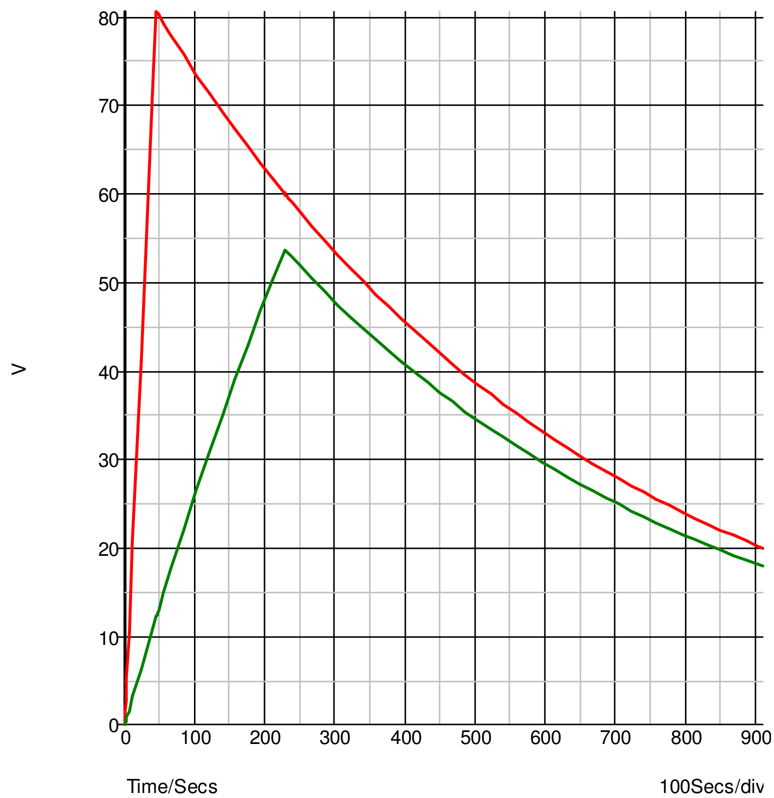
I did warn you I was going to make a whole bunch of assumptions!



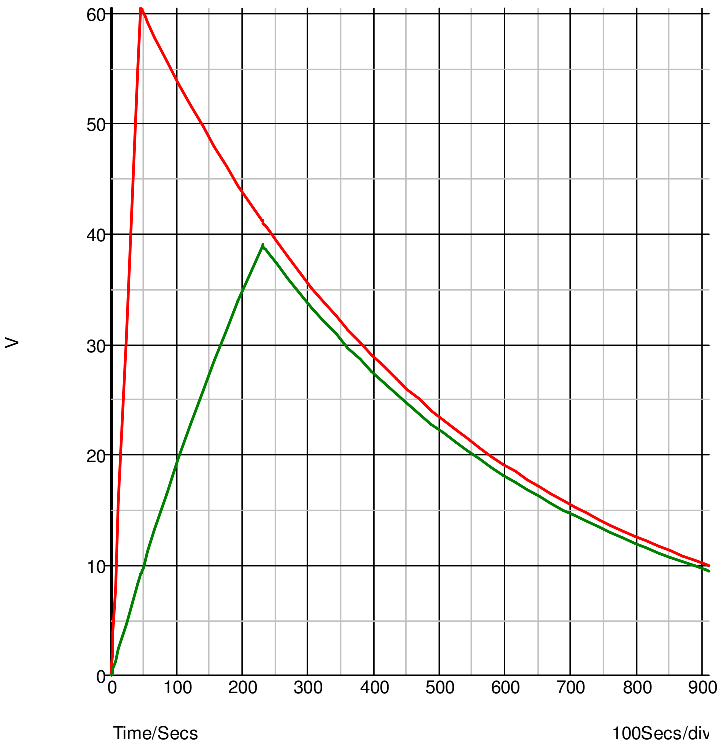
In practice the first simulation used 850A in the current source. Again I am not interested in the value, I just know I have to use 6.6× less for the low load condition, that is 128.8A. Rather than doing any boring maths (and/or actually having to think) I just simulated and tweaked the ON time of the current source until it hit the original curve (230s). I then backed it off a little to show the two distinct curves. The green (low power) curve has an ON time of 228s. Job done?

Well that is the sort of answer we want, but we have too many assumptions and no feel for the robustness of the solution yet.

Back to the simulator. Let's try peaking at 80°C (above ambient) and cooling to 20°C (above ambient). With a capacitance value of 620F and a current 1150A I get what I was after. Then I set the low load current to 174.2A and re-simulate. The ON-time was still set to 228s and the result is better than before.



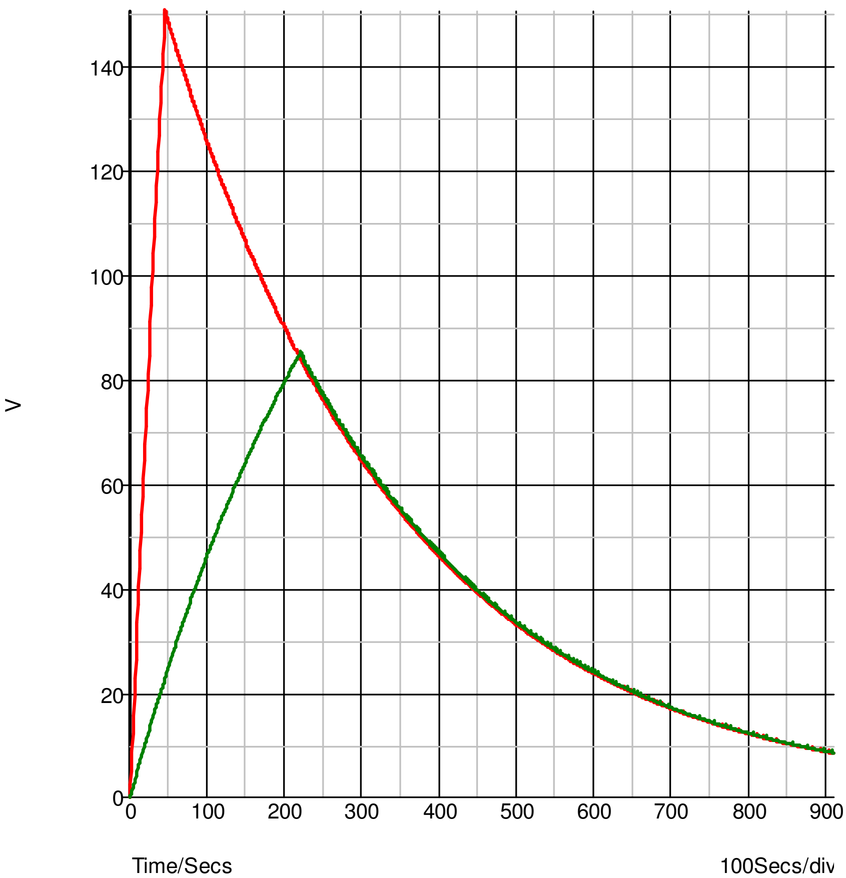
I can conclude that in any scenario where the 15 minute cycle gives a greater than 10°C residual temperature, my 230s ON-time is safe.



Now I have done this first pair of simulations based on an ambient temperature of 20°C. If my truck (which I don't own) was out on the plains (and I live in the UK where there are no plains) I would want the winch to work in a 40°C ambient, and frankly if the sun was shining it should be able to take 50°C. But we don't know how diligent our supplier is about adequately rating their winch. So let's see what happens on the simulation.

Starting from a 50°C ambient, with a 10°C residual at the end of the cycle, I am allowed to peak at 60°C. This takes 675A and 480F. And my 102.3A low load curve for 230s is still safe ☺

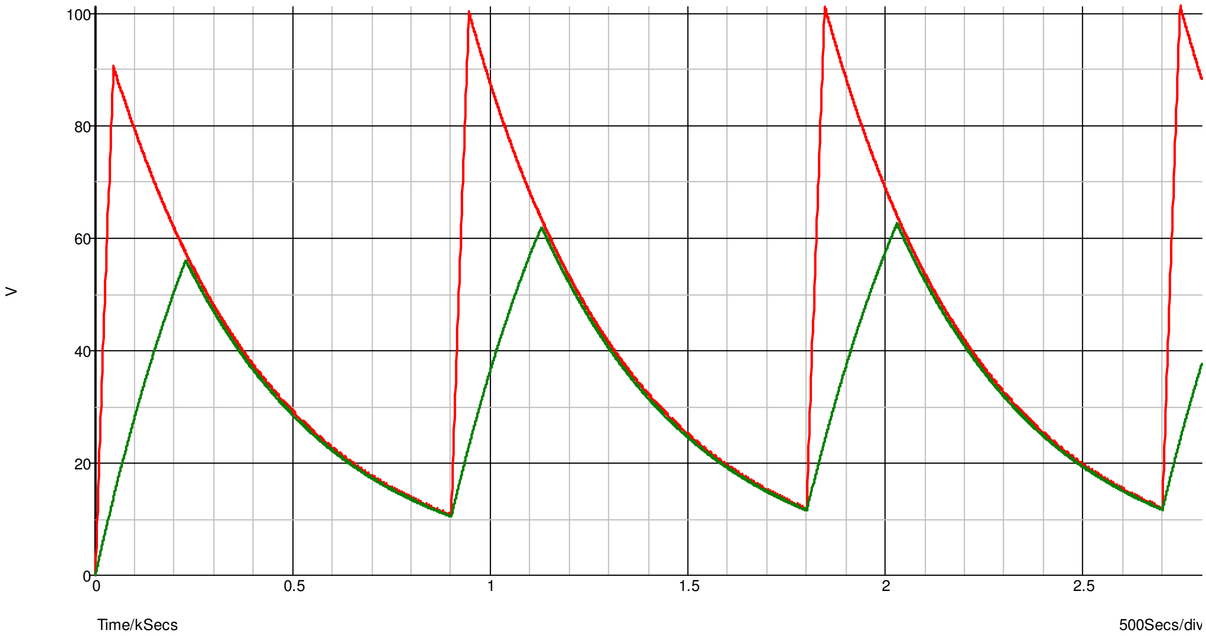
What is interesting here is that the change of test ambient by 30°C has made very little difference to the functional specification of the winch. Therefore the simulation has proved to be very resilient to the initial assumptions. We have a further assumption to test, namely the operating specification of the wire. High temperature 180°C wire is less common, but not unreasonable. My 20°C ambient assumption gave me a safer answer than the 50°C ambient assumption so I am going to stick with the 20°C figure. Sticking with the 10°C residual we can shoot up to 150°C.



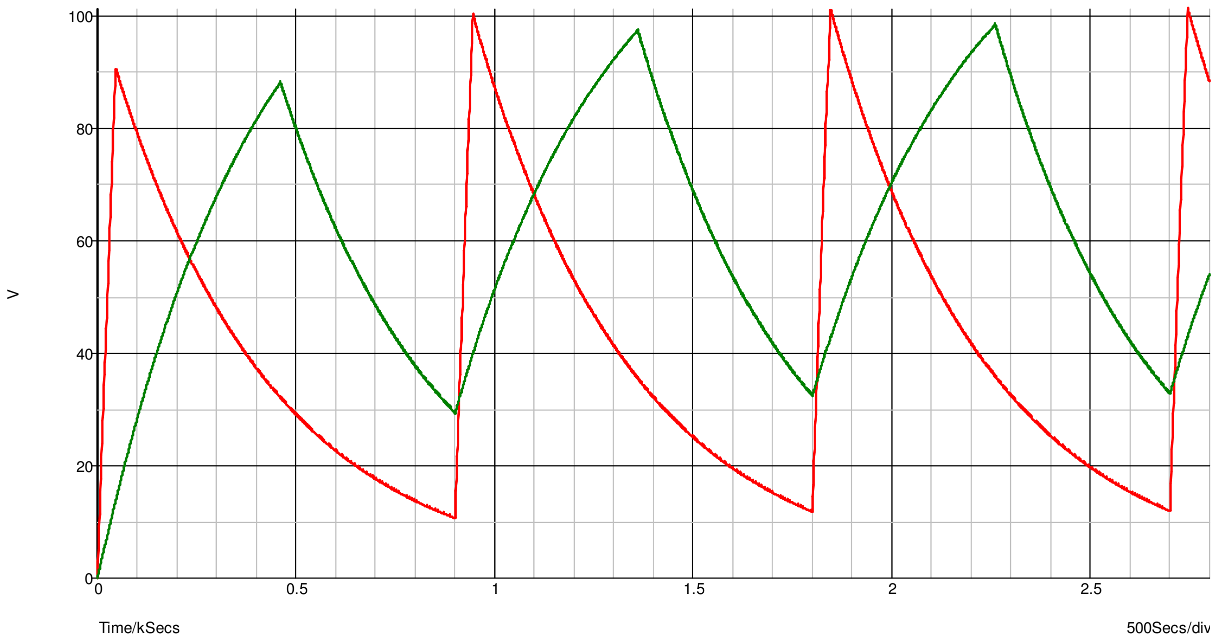
New values are 1080A, 300F, and 163.6A for the low load simulation. Now the 230s curve goes beyond the maximum load curve and the ON-time needs to be dropped down to 220s.

So 220s is a sensible value under all reasonable assumptions. But is it too conservative? And the answer is YES! The residual of 10° at the end of the cycle was for the highest load condition. The trouble is, as the residual gets bigger, we get more accumulation from cycle to cycle. But that is not a problem for the simulator. We just need to run more cycles.

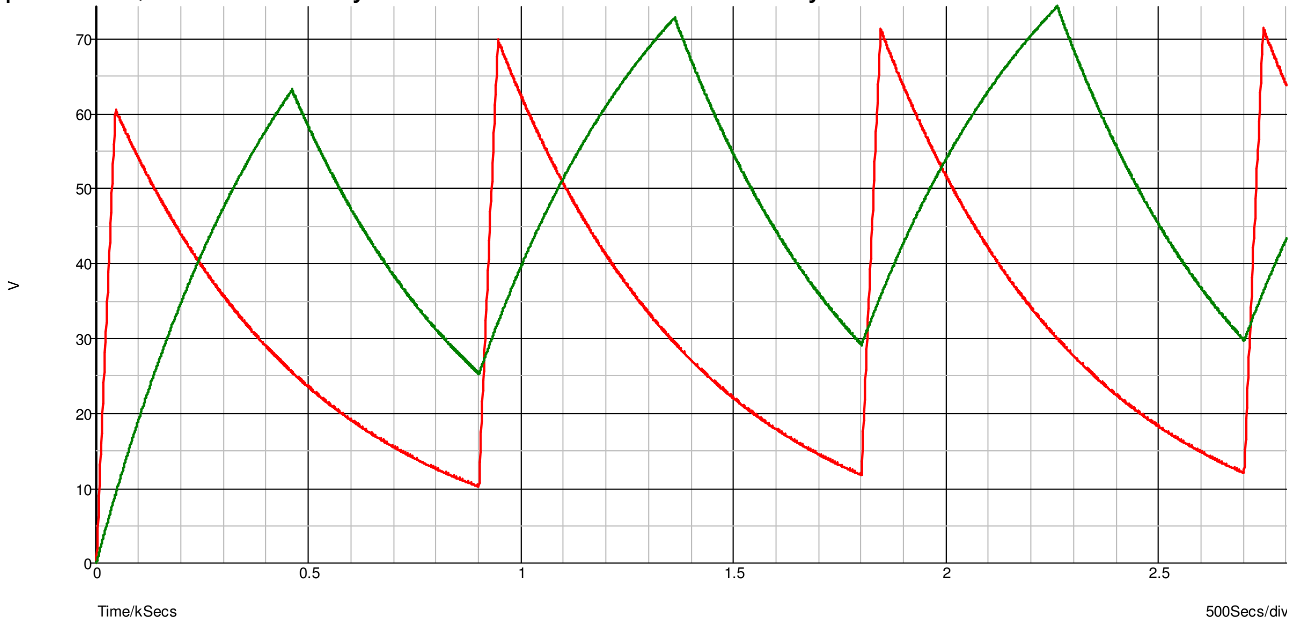
Let's start again for the 120°C wire. This time we can just type in the values we found from the previous simulation (850A, 400F, and 128.8A). You don't get much further change after the second cycle.



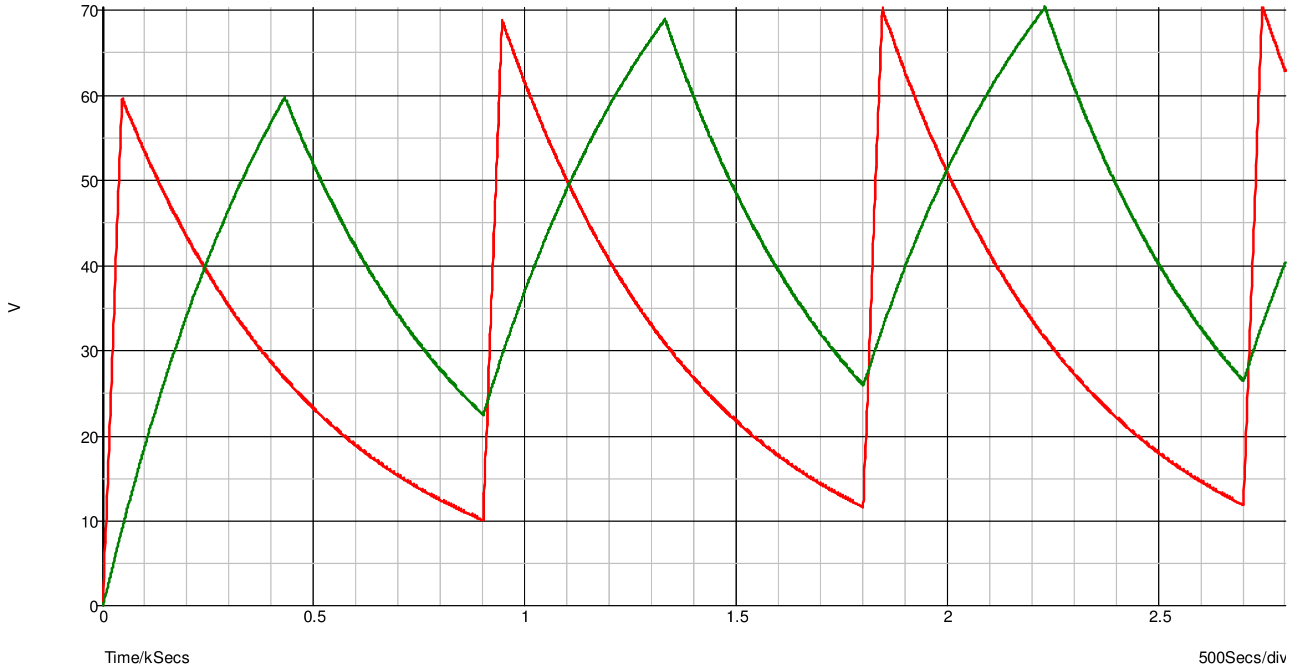
But the green trace is nowhere near the limiting value of 100°C! That is ridiculously over conservative. So we crank up the ON-time until it peaks closer to 100°C. Now we have 460s ON-time, a 2:1 improvement in specification from the earlier 220s value!



We also need to re-check the 50°C ambient condition. (480F, 675A and 102.3A). the requirement was to not peak above 70°C. Now the cycle-to-cycle accumulation is causing problems, but additionally the low load case is more badly affected.

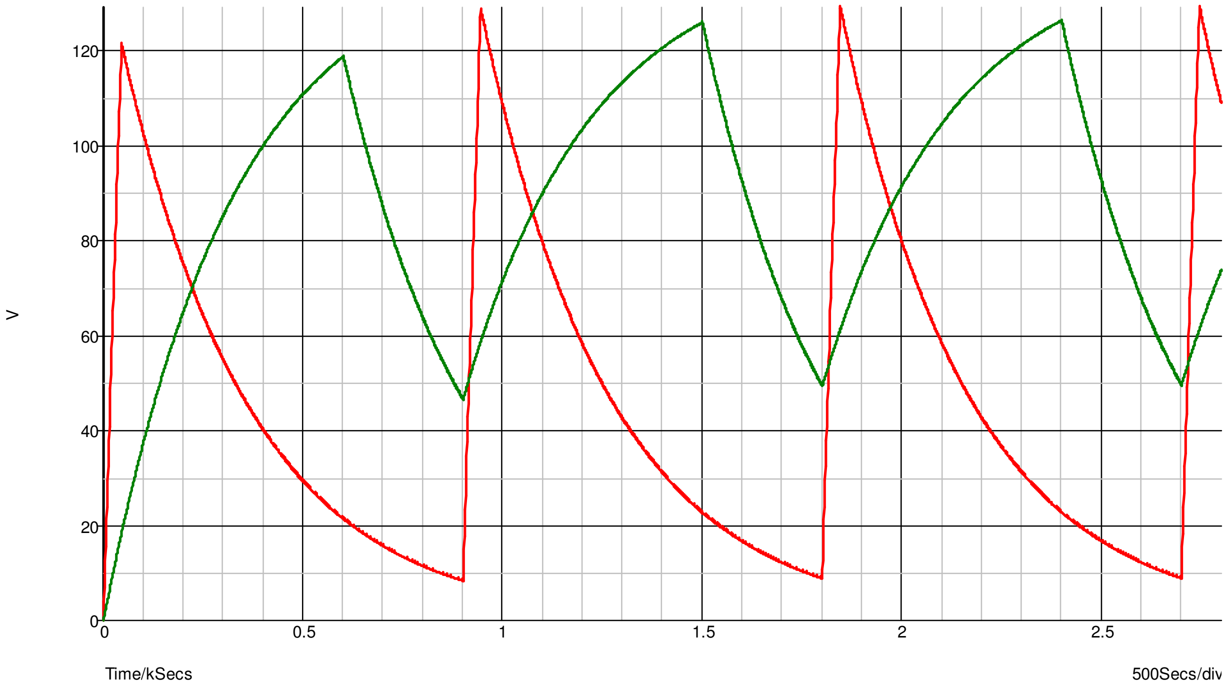


First we need to tweak the maximum load current down. 665A is better, giving 100.8A as the low load value. 430s is then acceptable.



On the first round of simulations the high temperature wire also made us back off our ON-time a little so we also need to re-run that, but this time with the 50°C ambient requirement as well. 50°C ambient with 180°C wire means a peak of 130°C in the simulation.

This simulation uses 320F, 925A and 140.2A.



The ON-time has increased to a massive 600s. Of course we can't rely on this because we don't know what sort of wire has been used. But it is not less than our previous 430s value, so the 430s value is confirmed as safe.

In Summary

Temperature is a killer of electrical equipment, but wire ratings are typically for thousands of hours. A short-term overload of a few degrees is typically not a big deal.

It has been suggested on the Eng Tips forum that because the spool length on the winch is only 50 feet then the ON-time is limited anyway. The interpolated load plot (shown earlier) gives the line speed at 250lb as 12 feet/minute. The spool run time is therefore limited to not more than 250s. (There is a little caveat in the data sheet that you mustn't pull a load without at least 5 full turns on the drum, so you can't actually pull the full 50 feet either.)

There are all sorts of problems with this setup. How do you know what the load is? There is no load gauge, so you have to see how much the winch is labouring and estimate the load. Suppose you are in an emergency situation and you have to clear a road of fallen trees. You are going to want to pull a load, and then pull another load in quick succession. But you can't because the duty cycle is then easily exceeded. The winch also has no locking mechanism, so if you are pulling something up a slope you can't stop half way and give the winch a rest. This winch is rated for *light duty* and you really have to understand that.

On the broader design front, I hope to have showed how you can effectively extract more information from a data sheet than is explicitly stated. Obviously the first step is to contact the manufacturer, but it is often the case that they can't or won't help. In this case you either have to specify a potentially much more expensive product or you have to use your engineering expertise to explore and enhance the data that you do have.