

Dynamic Line Rating – Thermal Line Model and Control

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Introduction

With the increased environmental awareness today, there is a desire to build new environmental-friendly power generation units and to increase the efficiency of already existing technology. Wind power is one such power generation technology that has seen rapid growth in recent years. An increase in wind power units and other renewable power generating units, especially decentralized power generation, will stress existing lines. Some grids may not even be prepared for a power increase at all. A solution would be to build new lines, but that is expensive and not always feasible.

Dynamic Line rating is a way of optimizing power throughput through electrical lines, by continuously looking at all factors that determine the surface temperature of a line and the rating of it, i.e. the amount of current it can carry. The continuous measurement of conductor conditions allow for an increased power throughput due to taking into account all factors affecting the surface temperature of a conductor. Normally, conservative values have been used to determine the rating of a line; however, additional weather parameters also influence the line rating. They include, in this thesis; solar heating, wind cooling, radiative cooling and current heating, which is a consequence of the current through the line. Wind power is ideal for use with dynamic line rating, since strong winds allows for high power output from the generation site, and also allows for more power on the grid, due to the cooling effect of the wind on the conductor.

E.ON wind is building a new offshore wind farm, Kårehamn, east of Föra on Öland, consisting of 16 3 MW wind turbines with a maximal output of 48 MW. The 50 kV-grid on Öland can currently only handle about 30 MW of that power without modifications [1]. That means the grid occasionally would become overloaded, where the surface temperature and resulting sag would reach unacceptable levels. With dynamic line rating, E.ON could more accurately determine the line rating and adjust the wind farm output accordingly. This will be accomplished through

three measurement stations, located at Köping, Högsrum and Linsänkan – which will have equipment for measuring weather parameters as well as either the current through the conductor or its surface temperature. A picture showing the northern part of the grid on Öland can be seen in Figure 1.

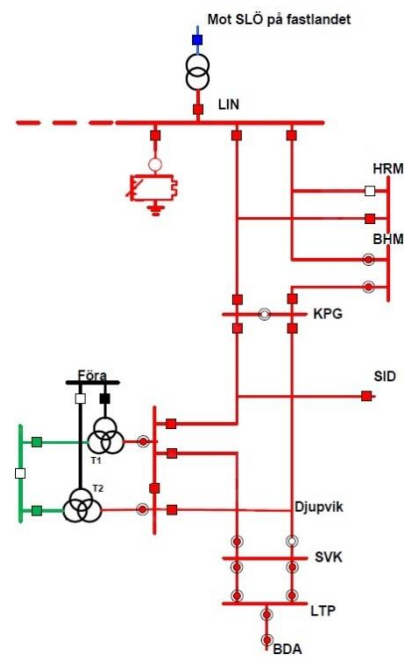


Figure 1. Northern Öland grid.

The main aim of the master thesis was to develop a Simulink model and control algorithm for controlling Kårehamn's output by sending a reference signal. It focused solely on the computer models and digital control, not any physical implementation. The reference signal, 0-48 MW, was produced based on the estimated current surface temperature of the conductor. Secondary aims included the ability to handle errors in the system and too high temperatures, as well as controlling additional power generating units, whose permission to be connected to the grid was decided by the current output of Kårehamn, as they have lower priority regarding network access.

Theory

The CIGRE 207 standard [2] was used to calculate the heat balance in an overhead line. Below is the heat balance, modified for use in this thesis.

$$m * c * \frac{dT_{av}}{dt} = P_J + P_S - P_C - P_R$$

Where:

m = Conductor mass density per unit length (kg/m)

c = Conductor specific heat capacity (J/ (kg*K))

T_{av} = Conductor average temperature (°C)

P_J = Current heating per unit length (W/m)

P_S = Solar heating per unit length (W/m)

P_C = Convective cooling per unit length (W/m)

P_R = Radiative cooling per unit length (W/m)

Normally, other parameters affecting the heat balance are included in the equations, such as corona heating and evaporative cooling. But they are commonly excluded.

Current heating is the heating of the conductor due to the effects of load current, solar heating the heating of the conductor as a consequence of incoming solar irradiation, the convective cooling the heat loss due to the wind cooling the conductor and finally, the radiative cooling is the process by which the conductor loses heat due to thermal radiation.

Simulink model

A flowchart for the complete Simulink model and its control can be seen below.

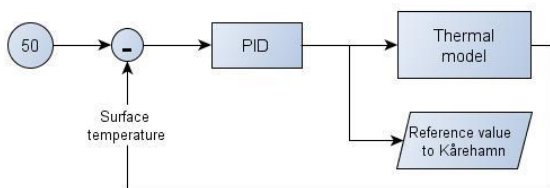


Figure 2. Flowchart showing the complete Simulink model with PID regulator, where 50 is the maximum allowed conductor surface temperature.

To the right is the thermal model, a modeling of the heat balance, which outputs the actual surface temperature of the most critical line. That value is compared to 50 °C, and the resulting difference is fed into the PID controller, which outputs an adjusted value. That value, in

MW, is sent as a reference value to Kårehamn, and also into the thermal model.

As stated, the thermal model block is basically only a modeling of the heat balance, where the heat gains and cooling gains are subtracted and integrated to produce the surface temperature. In the actual Simulink model there are also blocks which handle errors and additional power generating units.

The configuration parameters for the PID controller were chosen based on the slowest case, so it would handle all other cases in a stable, albeit slower, manner.

Table 1. PID parameters configuration.

| | Value |
|--------------------|--------|
| Proportional gain | 4.5 |
| Integral gain | 0.0075 |
| Derivative gain | -135 |
| Filter coefficient | 0.03 |

Alternate incremental control

The PID controller is compared to an alternative control method that was previously available. It worked by changing the reference value not continuously, but by changing it in small increments, with a short delay between changes. The model for this alternative design looks much like the one used in this thesis, but without the PID controller. A flowchart showing its basic design can be seen below.

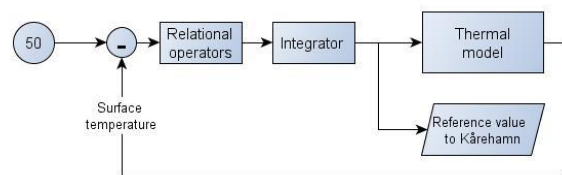


Figure 3. Flowchart showing Simulink model for alternative incremental control.

Here is a block "Relational operators" and "Integrator" instead of a PID. These handle the incremental changes to the reference value. All other aspects of this model are the same as in Figure 2.

Simulations and comparison

To test the model produced by the thesis and the alternative control and make sure they functioned correctly, simulations were carried

out. Different cases, with extreme conditions, were tested. Several simulations were carried out, where each time one of the following parameters was changing; wind speed on the conductor, wind direction, ambient temperature at conductor. Whilst the one was changing, the other two were fixed at an extreme value.

These extreme values were tested to make sure the reference value and surface temperature changed – which at normal conditions, they probably wouldn't. The values were: 0 and 15 m/s for the wind speed, 0 and 90 ° wind direction, -20 and 40 °C ambient temperature.

Below is an example of a changing signal during a simulation. Both step changes and ramp changes were tested. Ramp changes more closely mimic real life changes, while step changes better test the performance and stability of the control.

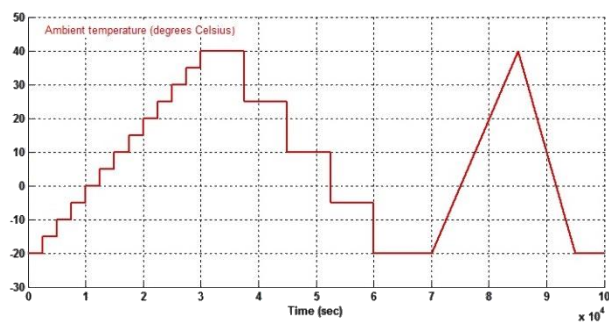


Figure 4. Example of signal used in simulations.

This signal for changing ambient temperature was tested for all extreme values regarding the wind speeds and directions. This article highlights the simulation with 15 m/s wind speed and 0 ° wind direction.

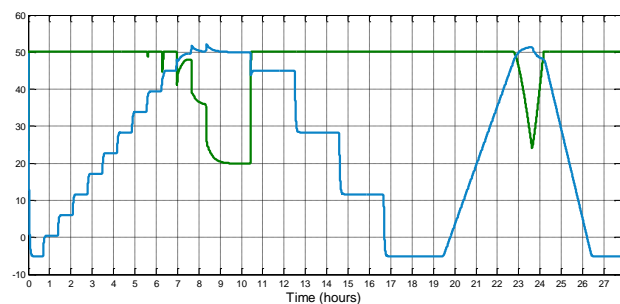


Figure 5. Result of simulation with the control method developed in the thesis.

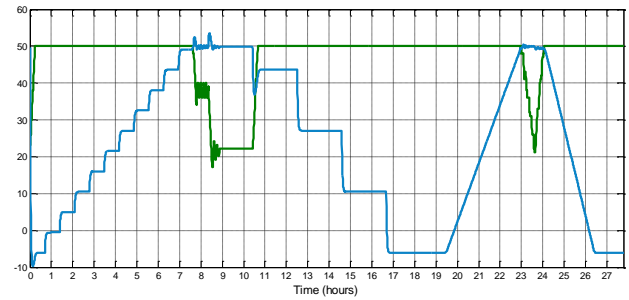


Figure 6. Result of simulation with the incremental control.

Both control designs clearly control the surface temperature, seen as the blue line in the graphs. It can also be seen that the reference value (green) is changing to make sure the surface temperature stays at 50 °C. In this case, as apparent in the figures, the difference in performance is not large, though the weaknesses of the alternative control can be seen – especially oscillations in the reference value.

Conclusion and discussion

The thesis produced a model which was constantly successful in limiting the surface temperature of the most critical of lines, by controlling the output from Kårehamn.

There was some cause for discussion however. Some of the simulated cases show excessive temperatures that can be questioned. The reason for these are unlikely combinations of speed and direction of the cooling wind and ambient temperatures. In reality, these cases are believed to be less relevant.

PID parameters were chosen with Simulink's built in tuning tools for a "worst case", but it's quite possible they could have been more suitably chosen, had different tools and more extensive knowledge been available.

When comparing the two control algorithms, that of this thesis' model and that of the alternative incremental one, it was clear the model constructed here was better. The main drawbacks of the alternative control were the severe overshoots and oscillations. Tweaking the size of the incremental changes and the delay would change its performance, but it was never as good as the control developed in the thesis.

Secondary aims were also met, with methods for handling two extra power generating units and

errors. Problems arose with the extra power though, as the way it was connected and disconnected were not always satisfying. Sometimes they would be disconnected, only to directly decrease the surface temperature which would cause them to connect again.

Sadly there were no real life values or cases to test the thermal model or control against. But when this control is implemented and tested in real applications with reality as test – it will be very exciting to see how it controls and to compare that to all the simulations made in this thesis.

References

[1]. F. Lundberg. *Smarta elnät klarar vindpark på Öland* [Online]. Available: http://www.nyteknik.se/nyheter/energi_miljo/vindkraft/article3651014.ece

[2]. Working Group 22.12, "Thermal behaviour of overhead conductors", Technical brochure #207, CIGRE, 2002.