Optimal control algorithms for klystron efficiency in ESS

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The use of X-rays has been known to society for over a hundred years. Neutrons can in a similar way be used to show screening pictures of objects, but the neutrons show other parts of the object. Neutrons give good pictures of carbon, nitrogen and oxygen, which are all important to life. They can also distinguish between different isotopes of hydrogen. These abilities together with the fact that neutrons do not damage sensitive samples such as living cells, makes it a great alternative for closer studies of for example proteins and DNA. It is also an important tool to make cancer treatment more efficient. With neutrons the image of the sick area will be sharper and more detailed, which makes it easier to only treat cancer cells and fewer healthy cells. Some other areas where neutrons can be used for research are alloys, biofuel, cosmetics, detergents, paint, nanoscience, medicine, food technology, combustion, packaging and geoscience.

As can be seen, neutrons can be used in many interesting research areas. Therefore it was decided to build a neutron source for research in Lund, Sweden. The research facility, named European Spallation Source (ESS), is planned to have 22 experimental stations where different material studies will take place. But how are the neutrons created and led to the experimental stations? Since neutrons are uncharged particles, they can not be controlled by electric fields and led to their goal. Instead, in ESS, a method called spallation is used. A beam of protons (which are charged particles and therefore easier to control) is accelerated to almost the speed of light and made to collide with a target. From this target, neutrons are released in all directions and some of them will end up in the experimental stations.

So, how does the acceleration of the protons work? The accelerator is made up of a number of cavities, which are a kind of resonator, or simplified they can be seen as pipes. The proton beam will go through these cavities. As we said before, protons are charged particles and are affected by electric fields. By putting the appropriate field in each cavity, the protons can gain more and more speed on their way through the accelerator. By the end of the accelerator the protons move with almost the speed of light.

To get the correct field in the cavity, a control system is used. The control system is there to make sure that the field follows the specifications, for optimal acceleration of the protons, that was calculated by the accelerator physicists.

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Figure 1. A picture taken of the same camera with two different methods. The upper picture uses neutron imaging and there the plastics (which contains hydrogen) in the camera are seen. In the lower picture, X-ray imaging was used and there the metal parts of the camera are seen instead.

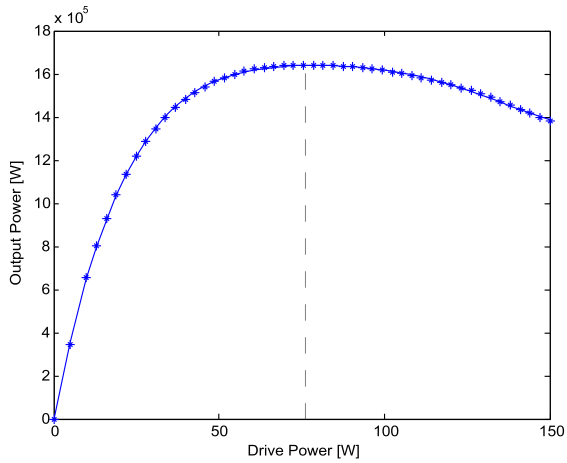

Figure 2. The amplification curve of the klystron

Whereas the control system can be designed in many different ways, the basics of it are always the same. It compares the actual value of the field with the value you want it to be, and then it takes some action to make them be the same. A simple example is cruise control of a car. Say you want to keep the speed 70 km/h. You can measure your speed by looking at the speedometer and if it shows that you are running in 60 km/h you press down the gas pedal (control signal) a little more, until the speedometer tells you that you have reached 70 km/h. It is basically the same with the electric field. If the amplitude is too low, you have to make the control signal bigger until the correct amplitude is reached and so on.

The control signal that is calculated is amplified in a so called klystron before it enters the cavity. To keep it simple the klystron is often thought of as a linear amplifier. However that is not really true, which adds some complexity to the overall system. The amplification of the klystron can be seen in Figure 2, where the control signal is the drive power on the x-axis, and the output that is sent to the cavity is the output power on the y-axis. To be able to see it as a linear amplifier you need to stay very low in drive power, but to get as high efficiency as possible in the klystron you want to stay close to the saturation point, marked with a dotted line in the figure. Every improvement of the klystron efficiency will reduce the waste energy a lot, and thus save both energy and money for ESS.

The work we have done compares two different control systems, the PI controller and the MPC controller, in their ability to keep the correct electric field in the cavities. The system uses the non-linear klystron mentioned above and the wish is to have it running on as high efficiency as possible.

The PI controller calculates its control signal based on the error between the actual value and the wanted value. If we return to the cruise control example the PI controller will see if you drive too slow and then increase the control signal. Next time you look at the speedometer you will know if you increased enough or maybe too much and then react on that information.

The MPC controller, where MPC stands for Model Predictive Control, is a little more advanced controller. The MPC has an inner model of the system that it uses to calculate the control signal. By using that model it can predict how the output will behave for different sequences of control signals and choose the best one. Let us return to the cruise control example once again. The MPC controller could for example include a model of the road you drive on. Then it can see if the car approaches an uphill, and start increasing the control signal even before the speedometer shows any decrease of the speed.

Since ESS is not constructed yet, the testing of the controllers was made by simulations of the system design. The result of our studies shows that both controllers can be used, with some modifications, to satisfactorily control the electric fields of the cavities. The MPC controller can be used with a high klystron efficiency, while the PI controller needs some further modifications to handle that case properly.

If you want to read more about this you can read the master's thesis with the same title and authors as for this article. More details are also found in the *ESS Conceptual Design Report* (February 2012), and the PhD thesis *Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities* by Thomas Schilcher at Universität Hamburg (1998).