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Integrated System Level Simulation and Analysis of DEMO with Apros

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ABSTRACT

The Demonstration Fusion Power Plant (DEMO) is the first fusion machine that is designed to produce electricity to the grid and be self-sufficient in tritium. This paper describes the modelling activities in the early stage of the project using Apros process simulation software. The structure of the model and the initial simulation results are discussed.

1 INTRODUCTION

The purpose of DEMO is to demonstrate that fusion is a commercially valid technology in electricity production. The conceptual design gains information from various studies and research activities managed by the EUROfusion consortium. Also knowledge from the ITER project, an experimental fusion reactor, already under construction in south France, with no power conversion system, will be utilized at the maximum extent as one of its main scopes is to demonstrate the technology necessary for a nuclear fusion plant [1]. In the modelled design the plant has a tokamak type reactor, a primary heat transfer system using helium (considered in the model up to now) or water as coolant, an intermediate molten salt circuit with a hot and a cold tank that functions as an energy storage system (ESS) [2], and a secondary steam cycle. The reactor is not modelled in Apros but its thermal power output is.

DEMO will operate in pulsed mode as is characteristic to tokamaks because plasma current can be induced only for a limited time. There is also an option for a DEMO steady state but this is considered premature in EU because of added complexity and risk. In the model it is assumed that the power cycle consists of a two-hour full power operation (burn phase) and a thirty-minute dwell time operation.

A system code called PROCESS has been developed to study DEMO plant concepts [3]. In 2014 a new model development task was started under the EUROfusion work package “Heat transfer, balance-of-plant and site” (WPBOP) using Apros simulation software. A year later another task was started under work package “Plant level system engineering, design integration and physics integration” (WPPMI). While the former task concentrates on the optimal process for electricity production, the latter has a more comprehensive scope. Systems outside the heat transfer and power conversion have more focus and the plant control is studied in a wider range of plant states including recovery from minor transient events. In this paper the early activities of the WPPMI are discussed and the initial results shown.

2 ELECTRICAL NETWORKS

DEMO will have two electrical networks similarly to ITER [4]. One of the networks is for continuously operating systems such as, e.g. the massive cryoplant systems, the cooling water pumps, the fuel cycle (tritium injection and reprocessing system), the vacuum systems, building ventilation and service system, i.e. the various auxiliary systems. This network is called the steady state electrical network (SSEN). The other network is called pulsed power electrical network (PPEN), as it supplies power to the magnetic systems: toroidal and poloidal field coils and central solenoid (TF, PF and CS) that induce the plasma current and confine the plasma in the vacuum chamber (torus). Plasma heating and current drive systems: neutral beam injector, ion cyclotron and electron cyclotron are also part of the pulsed power electrical network. It must be noted that since the conceptual design is still ongoing for DEMO there can be differences in the included systems. It is not decided whether DEMO will have all these heating systems or dedicated magnetic field correction coils for example.

The SSEN in the model contains two parallel trains. Both trains have four regular 6,6 kV and 0,42 kV bus bars and additional 6,6 kV bus bars reserved for emergency safety relevant systems and others for investment protection. The PPEN has three parallel supply trains with 66 kV and 22 kV bus bars. Helium circulators and pumps in molten salt and secondary steam cycle, that are part of the modelled processes, are connected to the SSEN. Other systems that are not modelled in detail, but have a large power consumption are included as load components so that their active and reactive power consumption can be modelled individually. In most cases the design has not evolved far enough to provide input and requirements for accurate modelling of these systems, but some estimation already exists about their power consumptions.

Figure 1 shows the active power consumption of CS and PF during the transition from burn phase to dwell and back to burn phase based on calculations in [5].

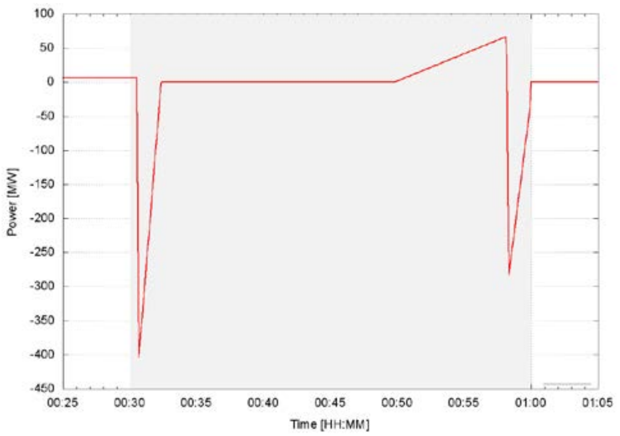

Figure 1: Active power consumption of CS and PF

The displayed power profile is calculated by multiplying the required voltage and current, which means that the power can have large negative values when the current decreases rapidly.

In figure 2 the gross and net power of the plant are displayed. The gross power is fairly constant because discharge of molten salt stored in the hot tank is used to keep the heat transfer to the steam cycle as constant as possible and thus the operation of the generator stable.

The electrical networks in the model do not yet have any systems in place to deal with drastic changes in the net power, so the distinct features of the PF and CS dominate the net power output.

It has been suggested that power peaks can be either dissipated or injected into the grid depending on the technical solutions of the power supply system [5]. This means that the true shape of the net power would be steadier than it is here.

In the figure the net power is higher during dwell time than during burn phase because in the early stage of the design process conservative assumptions are made regarding power requirements of different systems (particularly heat and current drive systems). During dwell time many systems are not used and so the internal consumption of the plant is reduced greatly.

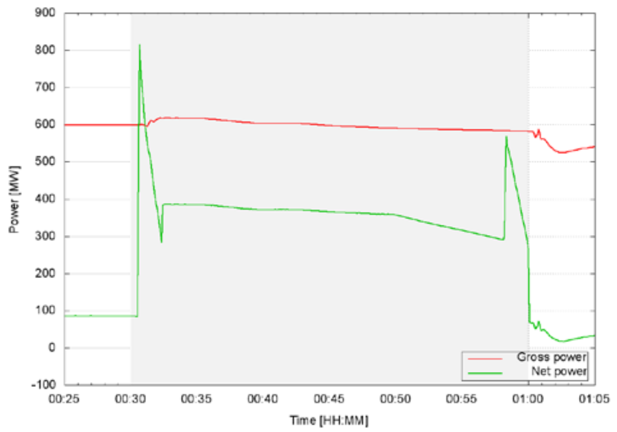

Figure 2: Gross and net power of the plant.

The electrical systems will be updated and refined continuously as the design matures and more information becomes available.

3 DWELL TIME OPTIMIZATION

The duration of dwell time depends on two actions that must be performed before a new burn phase can be started – a very low pressure level (high vacuum) must be re-established in the vacuum vessel by running vacuum pumps and the central solenoid must be recharged. In both WPBOP and WPPMI simulations a common assumption for the dwell time duration has been 30 minutes, but the design effort is focused to reduce the time necessary for the above-mentioned actions. In order to study how a shorter dwell time will affect the plant behaviour and what aspects must be accounted for in the modelling of especially the energy storage and power conversion systems in that case, simulations with shorter dwell times have been performed. Dwell times 20, 25 and 30 minutes were chosen as a set of conceivable values.

Assuming that the burn phase remains at two hours the inlet flow rate of molten salt hot tank remains also constant regardless of the dwell time. With a shorter dwell time, however, the discharge flow from the hot tank needs to be larger in order to preserve the mass balance of the hot and cold tanks. It is further assumed that a minimum flow in the charging loop during dwell time is bypassing the hot tank and directed to the economizer located before the cold tank in the intermediate cycle. Hence, the mass flow of hot molten salt (discharge flow) is recalculated to correspond to shorter dwell times according to Eq. (1).

$$\dot{m}_{discharge} = \frac{\dot{m}_{load} \cdot t_{pulse}}{t_{pulse} + t_{dwell}} \quad (1)$$

Scaled molten salt mass flows and tank capacities are shown in table 1.

Table 1: Hot molten salt mass flow and minimum tank capacity for different dwell times.

	30 min	25 min	20 min	unit
Mass flow of hot molten salt	4888	5056	5431	kg/s
Minimum molten salt tank capacity	$9{,}0 \cdot 10^6$	$7{,}8 \cdot 10^6$	$6{,}5 \cdot 10^6$	kg

A larger molten salt discharge flow also implies a possibility to have smaller storage tanks. At the same time the pump capacity must be increased. No other scaling in the intermediate circuit was done.

Most process parameters behave very similarly despite the process changes and only the base level is shifted. As can be expected, the net power production is higher when the dwell time is shorter and the mass flow is increased in the intermediate and secondary circuits (figure 3).

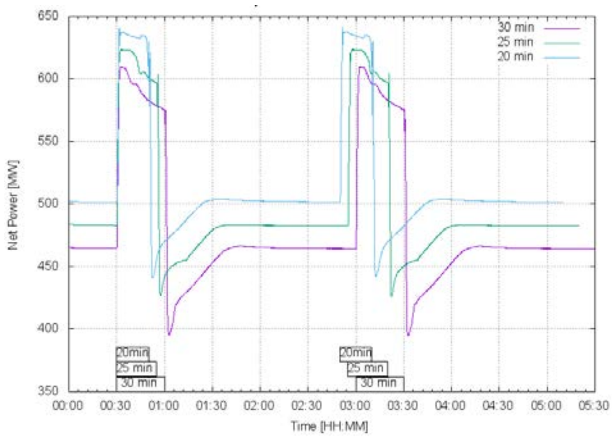

Figure 3: Net power with different dwell times.

4 FEED WATER FLOW CONTROL

Reducing the dwell time made it clear that the behaviour of the power conversion system is sensitive to the feed water pump parameters and the feed water flow in general. Therefore a further study was made on the effect of control method of the feed water pump.

In the model the feed water flow has been used to control the temperature of molten salt entering the cold tank. In the studied cases the feed water flow was instead used to: A) control feed water flow after preheating the feed water with divertor and vacuum vessel coolant circuits, B) otherwise similar to case A, but with changing steam pressure before the turbines, C) control steam temperature at the high pressure turbine inlet. For these analyses a model with updated process specifications was used.

In cases A) and B) the feed water flow is reduced to compensate the loss of heat load from the divertor and vacuum vessel during dwell time, but in case B steam pressure before the turbines is also reduced, which has a positive effect on the net power output. This improvement is caused by opened control valve in the steam line.

The net power with different control methods is shown in figure 4. In case A) the net power is close to the original (cold molten salt temperature control). In case B) the trade-off between burn phase and dwell time is clearly visible due to the reduced steam pressure set point. In case C) the power production is generally at a higher level but the process becomes very volatile. The fluctuations are even more notable in the molten salt temperatures.

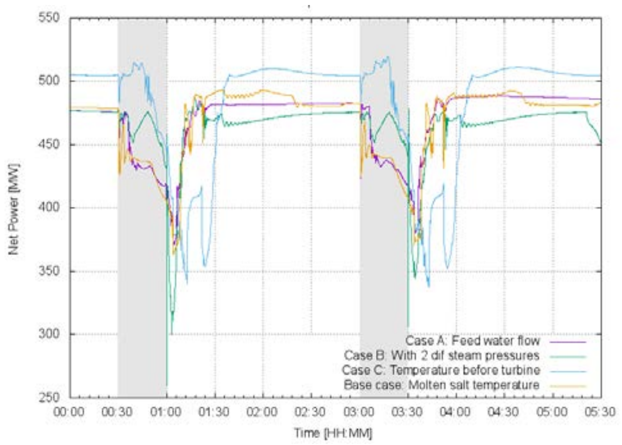

Figure 4: Net power production with different feed water control methods.

5 CONCLUSIONS

A task to develop a process model of the DEMO fusion power plant has been initiated in order to carry out simulations that can provide input for plant design decisions regarding the structure and parameterization of the plant. The model presented in this paper contains a helium primary heat transfer system, a molten salt intermediate circuit and a secondary steam circuit.

The level and stability of net electricity production are important factors in determining how well DEMO fulfils the requirements for a commercially viable power plant. This needs to be evaluated in both normal operating conditions and during transitions. Two electrical networks have been added for this purpose and the power consumption profiles of the major consumer systems have been modelled. The accuracy of the model will be increased when more information becomes available. This will also allow analysing the currents and voltages of the magnetic systems that are not present in other types of power plants.

The length of the dwell time has a direct effect on the net electricity production because during the dwell the absence of fusion power production must be compensated with the energy that is stored in intermediate molten salt circuit.

Simulations were done with different dwell times to study how the dimensions of the process are affected. On the one hand shorter dwell time requires smaller energy storage system and thus the total mass of molten salt can be reduced, on the other hand it necessitates larger molten salt mass flow rate in the discharge loop in order to preserve the mass balance in the molten salt storage tanks throughout several cycles. This in turn requires larger feed water and steam flow rates resulting in a higher electricity power production. However, the increased flow rates must be accounted for in defining parameters of key components and the increased flow rates also affect the transition behaviour of the plant between burn phase and dwell time, all of which must be accounted for in the control configuration.

Different control methods of the feed water flow were studied. When controlling the turbine inlet temperature the net power tends to keep at a higher level for a longer time at the beginning of the dwell period and most of the pulse period, but it takes some time at the beginning of the pulse to reach its high level and the fluctuations are significant. Controlling the feed water follow to compensate the loss of heat load from the divertor and vacuum vessel during dwell time provided improvement especially when the turbine inlet pressure set point was also changed. However, the improved power output during the dwell time meant that the output during the burn phase was reduced.

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