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STARTUP TIME REDUCTION FOR COMBINED CYCLE POWER PLANTS

Pascal Decoussemaeker, Anand Nagasayanam / GE Power

Brown Boveri Strasse 7, 5400 Baden, Switzerland
+41 58 505 96 37, pascal.decoussemaeker@ge.com

Wesley P. Bauver / GE Power

175 Addison Road, Windsor, CT, USA
+1 860 285 4238, wesley.bauver@ge.com

Luca Rigoni, Luca Cinquegrani, Glauco Epis, Marco-Ernesto Donghi / GE Power

Viale Tommaso Edison 50, 20099 Sesto San Giovanni Milano, Italy
+39 02243482186, luca.rigoni@ge.com

ABSTRACT

Combined cycle power plants (CCPP's) are highly efficient and have a high flexibility for fast load changes. Grid operators that have to deal with changing market conditions are therefore often using these plants to compensate for the volatility that has been introduced into the system by renewable energy sources. A particular scenario that is becoming increasingly popular is the use of Combined Cycle plants to provide non-spinning capacity reserves.

In order to provide non-spinning reserve, a fast and flexible startup is important. Depending on the requirements and the particular plant design, there are different options to reduce the startup time. This paper will start with an overview of the bottlenecks related to startup time reduction and will then provide an overview of the different ways around these bottlenecks. Finally, a few case studies will be presented of existing plants where upgrades were implemented to reduce the startup time.

INTRODUCTION

Combined cycle power plant technology is ideally suited to support a number of different operating scenarios. In Europe, we have seen them evolving from high efficiency base load operation to a cyclic operation mode to compensate for the volatility introduced into the grid by renewable energy sources like wind and solar. Fast back up power can be provided in different ways. One commonly used method is to run some of the plants on low load, ready to ramp up in case it is needed (Decoussemaeker, 2015). However, with an increased portion of electricity coming from solar and wind power plants, this would require a high number of plants to run in this less efficient operation mode for long periods of time. Since this is costly, and also leads to an increased specific CO2 emission, the preferred way to provide backup power is not to run on part load, but to shut down the combined cycle plant capacity that is not needed and keep them stand-by and ready to load when their support is required. This leads to power plants that operate only a few thousand hours per year. When a plant is shut down, it is often not known when a restart will be required. However, when it is needed, it is important to be able to provide load on short notice, within 30 minutes to 2 hours, depending on the local market set-up. This leads to a number of challenges for the operators of these plants, such as how to preserve the components during these long periods of inactivity and how to fast load a plant that has been preserved and shut down for some time. In addition, the asset condition management strategy needs to be modified based on a different set of failure modes.

This paper will deal with the challenge of fast and flexible starts after longer standstill periods. A total plant approach is used to design solutions, considering the interactions between various critical components in the plant. Changes are made to GT, HRSG, WSC and ST in order to achieve a faster and flexible start. A previous ETN paper has dealt with the review of the asset management strategy for cyclic operation (Decoussemaeker et al, 2014).

NOMENCLATURE

BOP	Balance of plant
DPT	Differential pressure transmitter
GT	Gas turbine
HRH	Hot reheat
HRSG	Heat recovery steam generator
NDT	Non-destructive testing
NFPA	National fire protection association
PED	Pressure equipment directive
PT	Pressure transmitter
SEV	Sequential combustion chamber
ST	Steam turbine
WSC	Water Steam Cycle
SEV	Sequential Environmental Burner

OVERVIEW OF THE STARTUP SEQUENCE

Before identifying how to optimize the startup time of the combined cycle power plant, it is important to understand the different phases of the startup. The details of the startup sequence will differ from plant to plant. The example in this paper is based on a typical sequence of the General Electric GT26 (See Figure 1).

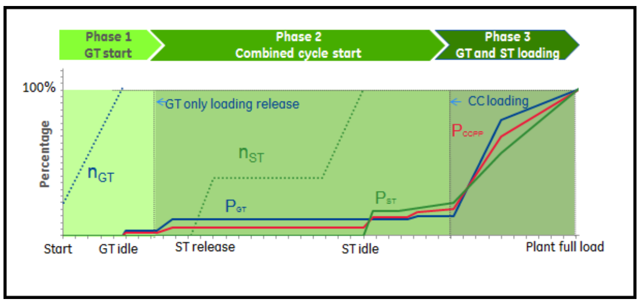

Figure 1: Typical cold start sequence

The above figure depicts a typical cold start. During the first phase, the gas turbine (GT) is started and synchronized. Before the GT can start, all systems on the plant need to be ready to go. This means all auxiliary and BOP systems need to be operational and the HRSG drum levels need to be on startup level. The GT sequencer then goes through a purge sequence, ignition, run up to idle, synchronization and loading to minimum load. Once minimum load is reached, the next phase can only be released when sufficient vacuum is built up in the condenser to release the steam by-pass system. This requires gland steam and motive steam to draw vacuum with the startup ejector. Typically, once the pressure is below 300 mbar, the intermediate pressure steam by-pass system can be released.

After the start of the GT in phase 1, the steam turbine (ST) startup is the focus in phase 2. At the start of phase 2, the GT is loaded to a load that is low enough to start the ST. For the GT26, this is just below the SEV switch on. The ST run up typically requires live and reheat steam temperatures at 400°C. It is also necessary to wait until the steam temperature, pressure and quality are within the required limits. Once this is achieved, the ST run up is initiated. Typically there is a ST warm up stop during the run up to manage the ST stress levels. The next phase is released when the ST is sufficiently warmed up and the steam temperature can be controlled for an unlimited loading.

In the 3rd and last phase, the GT and ST are loaded based on the gradients defined during the design of the GT, ST and HRSG.

Sample of approximate time (in minutes)	Phase 1	Phase 2	Phase 3
Cold	20-25	80	45
Warm	20-25	50	45
Hot	15-20	10	20-25

Figure 2: Typical duration of the times for the different phases

Figure 2 gives an indication of typical time (in minutes) required for the different phases of the startup. This table shows that the depending on the expected type of start (cold, warm or hot), the main focus of the startup time reduction effort, for a particular installation, may be on a different phase of the startup. Through pre-heating or by keeping the unit warm, it is also possible to move from one category into another. The following chapters will provide additional detail on how to reduce the duration of each of the 3 phases.

PHASE 1: GT STARTUP

In phase 1, the GT is started, synchronized and brought in a stable situation with a minimum load. There are different ways to reduce the length of this first phase:

- Reduce the time to the GT start release;
- Purge credit;
- Improvement of the condenser evacuation.

A time consuming activity is the adjustment of the HRSG drum levels prior to startup. Preserving the HRSG with water in the drums can save a lot of time. This can be achieved with either nitrogen blanketing or by keeping the HRSG warm. Warm keeping can be achieved with a stack damper for shorter periods, like a weekend, and with sparging steam for longer periods. Keeping warm does not only help in this phase, but also reduces the time required for phase 2 and phase 3. For more details, see section on preservation further in this paper.

Another option to reduce the startup time is to release the first part of the GT or plant startup sequencer already before the water steam cycle startup release is available.

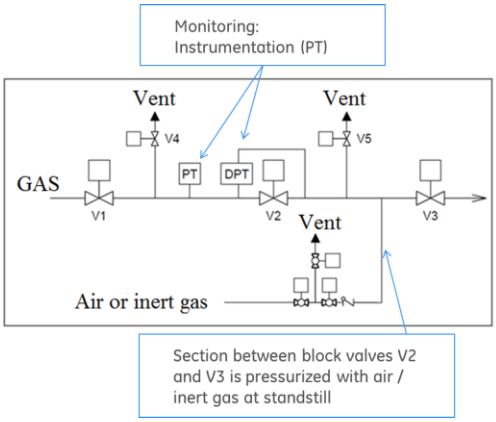

Figure 3: Purge credit

Part of phase 1 is also the HRSG purge by means of a GT motor roll in order to make sure that there are no combustible gasses left in the HRSG. The NFPA85 guideline is usually used as the standard for this purge cycle. The standard requires a purge volume of at least five times the HRSG volume and a purge time of not less than 5 minutes. This does not only require the additional time needed to perform the purge, but it will also require a longer heat-up time later in the startup cycle to compensate for the energy lost because of the cool down during the purge cycle. In addition, it requires also auxiliary power to roll the GT and may also lead to premature ageing caused by condensate flooding of the lower headers (Decoussemaeker et al, 2014). In the 2011 revision of the NFPA85 guideline, it was recognized that a normal GT shutdown does not result in a hazardous atmosphere. Therefore, a GT purge is not required for the subsequent startup, provided that the purge condition can be maintained. For gaseous fuels, this can be achieved by means of a triple block and bleed of the fuel supply, with a pressurized section. As long as the positive pressure can be maintained, the purge credit remains valid (see Figure 3). This will reduce phase 1 of the startup by 5 to 10 minutes

Phase 1 ends after the synchronization of the GT and GT loading to minimum load, when a stable condition is achieved. This is the case when the steam by-pass system has taken over the pressure control of the HRSG. In order to start the steam by-pass operation, vacuum in the condenser is required. Condenser vacuum requires steam to operate the air ejectors and the ST gland steam system. If an auxiliary steam source is available, condenser vacuum can be drawn ahead of time.

PHASE 2: COMBINED CYCLE STARTUP

Once the steam by-pass is in operation, it becomes possible to further increase the GT load and produce sufficient steam to start and synchronize the ST, but not too much in order to limit the inlet steam temperature. There are different ways to reduce the length of this second phase:

- Reduce waiting time for the steam quality;
- Pre-warming of the ST;
- Optimization of the plant startup concept;
- Startup the GT without waiting for the ST.

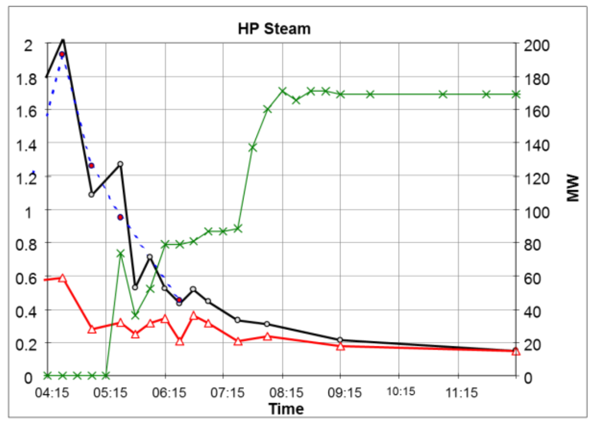

Figure 4: HP boiler steam cation conductivity (µS) during startup of ST (black (○) = measured, red (△) = calculated without CO2, Green (✕) = MW), blue (○) = calculated for all anions)

Especially for a cold start, a large part of the waiting time in phase 1 is the time required to achieve the right boiler water and steam quality. Clean steam is important for the lifetime integrity of the ST. But also the feedwater needs to be clean, since it will be injected into the steam through the desuperheater. The cleanliness of the steam is expressed by the conductivity. In case the cycle has been de-pressurized, CO2 will have entered the system with the air and this will lead to higher conductivity values. It will require some time until all CO2 is purged from the system (see Figure 4). The removal rate depends on the efficiency of the deaeration devices (deaerator and condenser). Cyclic units with frequent cold starts require a significant proportion of the operating time to reach normal values. This time can be reduced by installing a degassed conductivity measurement. Such an instrument will measure the conductivity of the sample after removal of the CO2. There are two widely used techniques for degassing: gas stripping with nitrogen and heating up to near boiling point.

Another steam quality related issue is the length of the sample lines from the sampling point to the instrument. It takes time for the sample to reach the instrument, especially during the startup phase, when the pressure is lower. This can be improved by installing a back pressure regulation valve to maintain sampling line pressure at lower water/steam system pressures. Further improvement can be achieved by installing a remotely controlled purge valve (Sigrist, 2014).

However, in case it is possible to keep the air out by means of keeping the unit warm or using a nitrogen blanket, there will be no ingress of CO_2 that will increase the conductivity and also there will be less iron oxides from corrosion during the standstill period.

It is also important to have a closer look at the start-up sequencer and optimize hold points, controllers for the steam by-pass system. Also it is important to ensure that activities that can be done in parallel are not executed sequentially. Examples include optimization of the ST sequencer, pre-warming of the steam piping, automation of manual drives…

For a cold start, the longest waiting time is related to the warming up of the ST in order to avoid excessive stress. If the ST can be pre-warmed, this time can be shortened. This can be achieved by injecting hot air into the ST (see Figure 5), either in an open loop or in a closed loop.

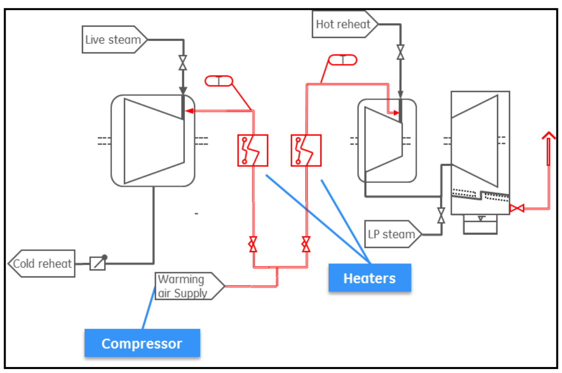

Figure 5: ST pre-warming

If a plant is restarted to provide backup power to support the grid in case of sudden power shortages, it is important to be able to bring as much as possible power to the grid in the shortest time. In this situation, fuel efficiency is of secondary importance. If this is the case, a possible scenario is to load the GT as much as possible, without waiting for the ST. However, if the ST is added at a later stage, the steam temperature will have to be reduced. This can be achieved by adjusting the GT inlet guide vanes. If however this is insufficient, it might be necessary to add desuperheater capacity, either by adding an interstage, or an end-stage desuperheater or by upgrading the existing installation. The interstage desuperheater capacity may be insufficient because of insufficient thermal head. Once the steam temperature reaches the saturation temperature, additional water will no longer evaporate. This condition is called overspray. To prevent overspray, the remaining superheat downstream of the water injection should not drop below 28°C (50°F). It is further important to make sure that when the amount of water is increased, there is sufficient downstream pipe length to ensure a complete evaporation of the water before the first bend in the steam piping. To reduce the risks related to overspray or incomplete evaporation, it is recommended to install skin thermocouples on the top and bottom of the steam piping downstream of the desuperheater to monitor for any water accumulation.

Another method to uncouple the GT loading from the ST loading is by cooling through injection of ambient air after the GT and before the HRSG. This method has the advantage that it not only cools the steam, but also the structural components, preserving the lifetime integrity of the HRSG.

PHASE 3: LOADING

Once the ST is warmed up and the steam temperature can be controlled for unlimited loading, the combined cycle plant can be loaded to the required load. There are different ways to reduce the length of this third phase:

- Increase the GT loading gradient;
- Pre-warming of the ST.

If the gradient of the GT is increased, thermal fatigue life consumption on the HRSG will be higher depending on the thermal state of the HRSG (Decoussemaeker et al, 2014). Depending on the operating history and the potential commercial benefit of the opportunity, it might be worth to perform a faster and flexible start. A trade-off between lifetime consumption and the income of the opportunity needs to be made with a fatigue lifetime calculation for the critical components. The HRSG components most at risk of failure are thick walled components subjected to rapid temperature and pressure changes and of complex geometry. These typically include the HP superheater and reheater outlet manifolds and headers and the HP drum down comer nozzles. The calculation is usually done based on the European standard EN12952.

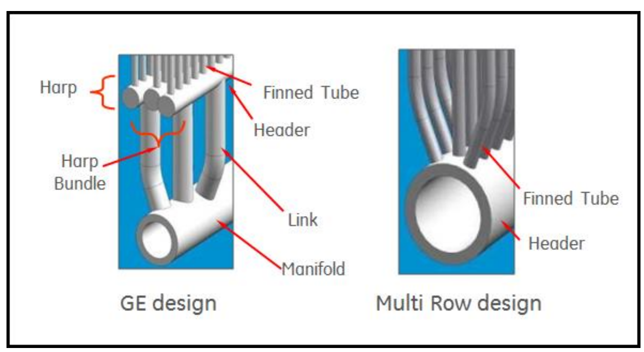

Figure 6: Pressure part design

Fatigue life consumption depends on the design. Small diameter headers, in conjunction with smaller incremental step changes in pressure part wall thickness, lead to minimal tube-to-header temperature differences at the weld joint, reducing the fatigue loading. The use of a single row harp leads to such a stepped wall thickness change and eliminates the bend in the tube near the header. This design therefore permits more rapid rates of temperature change than more conventional thick-walled headers used with multi-row harps (see Figure 6).

Pre-warming of the HRSG will reduce life consumption. The lifetime consumption per cycle can be either calculated in advance for typical cycles, or can be determined by means of an on-line monitoring system. When increasing fatigue life consumption, it is important to supplement the theoretical calculation with on-site NDT at the most critical locations. In case especially critical components are identified, the code calculation and NDT should be supplemented with a finite element life assessment.

In order to avoid ST trips or meet the ST requirements, additional DSH capacity is also required.

PRESERVATION OF THE HRSG

When the plant is often shut down for long periods of time and it is not clear when the unit has to return to service, preservation of the HRSG becomes a specific challenge.

A question that is often asked is “how long can I wait”? There is no right answer to this question because corrosion does not wait. There is no “grace time”. Corrosion starts as soon as the conditions for corrosion are met. For the water side this is as soon as there is oxygen ingress into the system and for the flue gas side this is when the temperature drops below the water dew point and the relative humidity is not below 35%. Some corrosion in the HRSG will however not immediately lead to a failure of the component. However, iron oxide particles on the water side will lead to an increase of the conductivity and will lengthen the waiting time for the right steam quality in phase 1 of the startup. In addition, the deposit loading in the evaporator circuits will increase which in turn increases the risk for under deposit corrosion (Decoussemaeker et al, 2014). Iron oxide particles may also cause deposits on the ST and deposits and erosion on water or steam valves. Corrosion on the flue gas side may lead to fin spallation (see Figure 7), leading to an increase of GT back-pressure and a reduced heat transfer from the gas side to the water/steam side. An increased GT backpressure reduces the GT efficiency and the maximum power capacity.

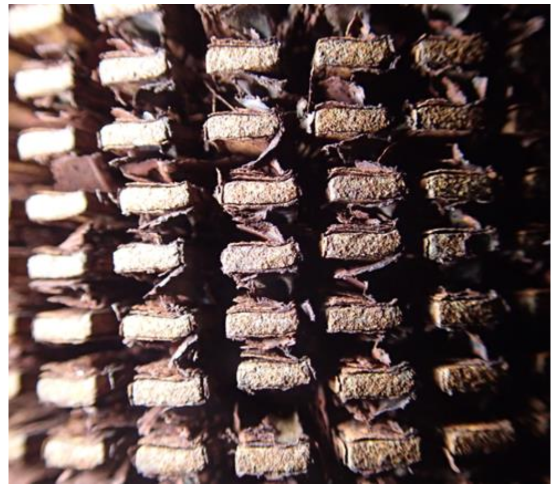

Figure 7: Flue gas side corrosion of finned tube.

In case a quick return to service is required without a lot of advance notice, it is important to maintain the water at the right level in the unit. To avoid corrosion, ingress of oxygen on the water/steam side needs to be avoided and the water/steam chemistry needs to be maintained. This can be achieved either by keeping the unit pressurized with a nitrogen blanket or by keeping the drums warm with sparging steam in the evaporator. Keeping the unit warm will not only reduce the corrosion risk, but as discussed earlier in this paper, it is also a very effective way to reduce startup time.

Keeping the unit warm for a shorter time period, e.g. a weekend, can be achieved by means of a stack damper (see figure 8). A stack damper should be combined with good cold end insulation and it is also important to minimize water losses, not just from open or leaking drains, but from all sources. Often forgotten are for example the chemical sampling lines. A good upgrade is to install an automatic shut off for the sampling lines (Sigrist, 2014). This also reduces the EHS risk of getting nitrogen from the HRSG preservation in the sampling container. In case a stack damper is not part of the original design, it may be difficult to retrofit, if the stack system has not been designed for this additional weight. A possible alternative is a stack balloon. In this case, it is however important to go for a system that deploys automatically. Manual systems are only recommended for longer shut down periods.

Keeping the unit warm and pressurized for longer time periods can be achieved with sparging steam. Sparging steam is usually injected through the bottom header or manifolds. This requires either an auxiliary boiler or another steam source, e.g. another unit that is in operation.

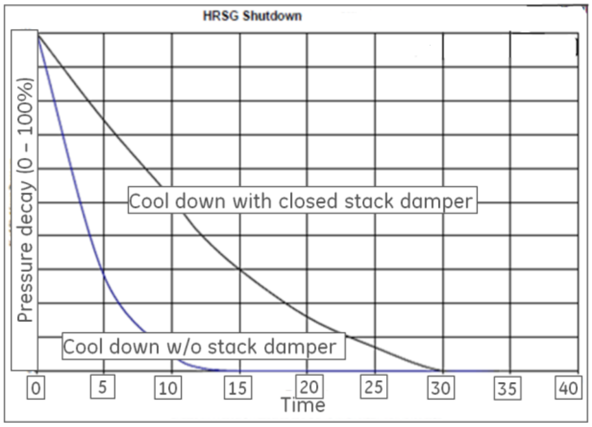

Figure 8: Pressure decay after shutdown

On the flue gas side, a stack damper is required to maintain the heat as long as possible. When the temperature drops below the dew point, a dryer has to be connected to maintain an ambient relative humidity of less than 35%.

An alternative method to preserve the water/steam side is gaining interest. Film forming amines are organic chemicals that form a protective film on the metal surface. If they are dosed during operation, they will provide protection when the unit is in stand-still. The general feedback of the industry show positive results and EPRI studies show significant reductions of iron oxides after periods of shutdown of units protected by means of film forming amines compared to reference cases. It is however difficult to say when there has been sufficient filming in the complete system to allow for a comprehensive protection and how long the film will remain active. It is therefore recommended to carefully monitor results and side effects when these chemicals are introduced and also to use it in combination with the existing proven methods (IAPWS, 2016).

CASE STUDY 1: KA26-1 UPGRADE IN EUROPE

In order to provide grid support, the requirement for this plant is to be able to start at any time (hot/cold/warm) and provide 180MW within 30 minutes. To achieve this, the GT is started and loaded with the ST on by-pass. Later, the ST is started and taken on-line. To achieve this, the ST is pre-warmed, the GT exhaust temperature is reduced by means of a new operation concept for the inlet guide vanes and the set-points for the HP/IP desuperheaters have been updated

Although it takes now longer to start up the complete plant, and also the specific fuel consumption for a startup has increased, this modification allowed this plant to participate in the market for ancillary services (see Figure 9).

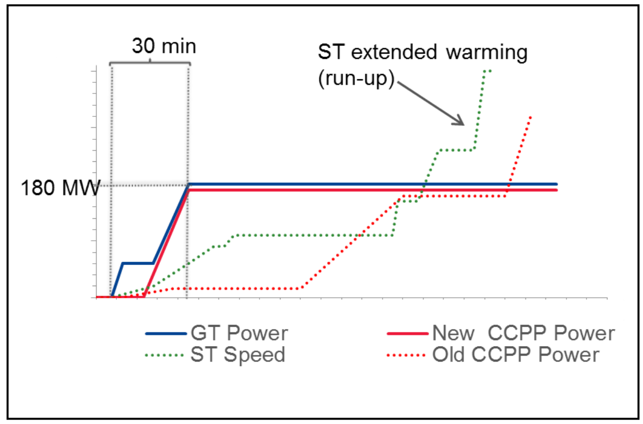

Figure 9: Loading concept, before and after

CASE STUDY 2: KA26-2 UPGRADE IN EUROPE

Another GT26 planned in Europe needed to be able to achieve GT full load condition within 45 minutes at any time (cold/warm/hot) on short notice. In order to achieve this, the purge credit was implemented and condenser evacuation was initiated before steam production started. Because of this, steam flow could be established through the steam by-pass system at a much earlier stage. Because of these changes in the by-pass operation concept, it also became possible to start the GT loading and the ST run up at an earlier stage. In addition, also the GT loading gradient was increased and the HRSG level control was improved (see Figure 10).

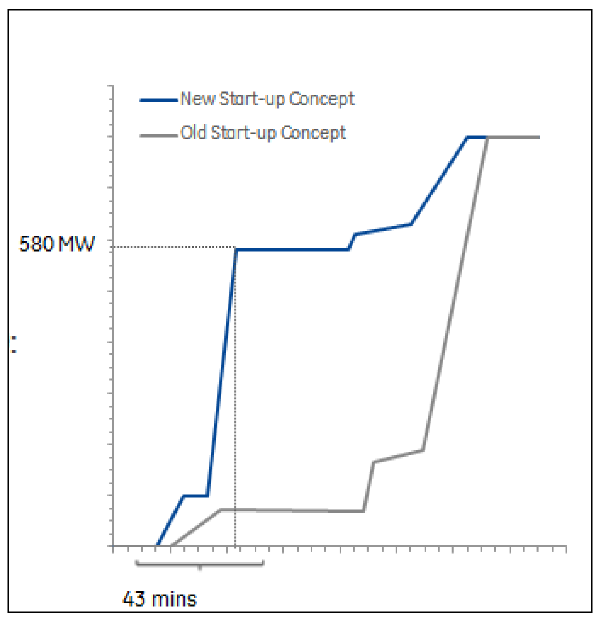

Figure 10: Loading concept, before and after

CASE STUDY 3: COMBINED CYCLE PLANT IN ITALY

For another case in Italy, the market demanded a start-up time of less than one hour. This plant is equipped with two HRSGs linked to a common ST. The bottlenecks in the start-up rate were the HRH steam lines, which needed a warm-up time of more than two hours. In order to reduce this warm-up time for the HRH lines of both the HRSGs, new warm-up lines were designed and installed. The project included:

- Development of a transient thermal model of the HRH steam lines, in order to determine the required size of the new warm-up lines to heat HRH lines from 300 °C to 450 °C in 30 minutes over the entire length (see Figure 11);
- Basic and detailed engineering of the new warm-up lines, starting from the new nozzles on the existing HRH lines, before the HRH stop valves, up to the new common expansion vessel and relevant vent line and silencer. Each warm-up line is equipped with a zero leakage motorized control valve and 2 manual stop valves. Particular care was taken during the design of the new warm-up lines and in the valve selection, due to the high steam velocities inside the pipes;
- Due to the high steam velocity inside the warm-up lines, a noise study was performed to correctly design the silencer, the expansion vessel and the thermal / acoustic insulation and meet the noise emission limits of the Italian law;

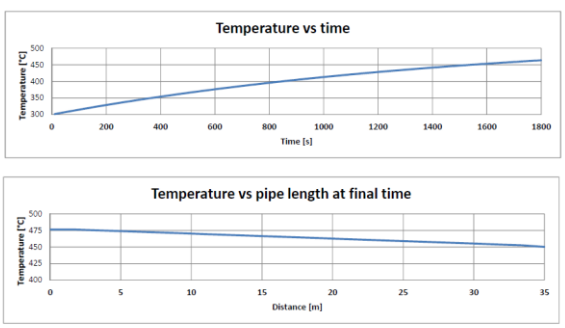

Figure 11: thermal transient calculation of one HRH line

- Design, manufacturing and installation of new steel structures, supporting the new warm-up lines, according to the Italian law;
- Manufacturing , installation and commissioning of the new warm-up lines and relevant equipment (such as valves, silencers), according to PED (see Figure 12);

Figure 12: New warm-up HRH steam heating lines

- PED assessment, including lifetime assessment and certification of the modification, according to the Italian law;
- Commissioning and tuning of the system.

After installation and commissioning, a successful performance test was performed:

- HRH lines heating time was reduced from more than 2 hours to 30 minutes (see Figure 13);
- Noise emissions are kept under 85 dBA.

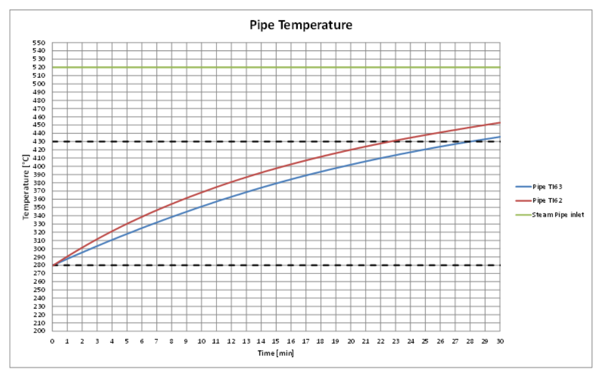

Figure 13: Performance test results

The reduced fuel consumption associated to this modification lead to a project payback time of about one year.

CONCLUSION

For many combined cycle operators, the capability to perform a fast and flexible startup at any time is an important capability that allows him to generate extra income. This paper has shown that it is possible to significantly reduce startup times. Typical time reductions that can be achieved are 60 minutes for cold starts, 30 minutes for warm stats and 25 minutes for hot starts.

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