CCPP improvements in a business environment of intermittent power generation

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1 Introduction

Electricity markets with high levels of renewable power generation are typically forcing radical changes on the fossil fuel power plants operating in these markets, strongly affecting their number of operating hours as well as their operating profile. Many combined-cycle power plants (CCPP) designed for base-load operation are having to change to cycling mode, requiring optimized startup performance after overnight stops. As renewable electrical generating capacity continues to rise, renewable power generation during advantageous weather conditions is leading to periods without CCPP dispatch lasting several days or even weeks. In general, the consequences of these extended shutdowns are longer plant startup times and moderate power ramp-up due to the low metal temperatures of the heat recovery steam generator (HRSG) and steam turbine. To increase the power availability of CCPPs after shutdowns of differing lengths, a number of improvements including variable gas turbine operating modes have been developed and tested, and are presented in this paper. It will be shown that it is possible to adjust startup capabilities of the CCPP fleet in service to changing market requirements.

The solutions presented here are part of the Flex-Power Services™ portfolio which Siemens is continuously expanding to enhance the capabilities of fossil-fired plants (Figure 1) to partner up with renewable energy sources.

![Figure 1: Aspects of Flex-Power Services™](image)

2 Fast load gradients

To balance the volatile nature of renewable generation, the fast power response of fossil-fired plants is an important flexibility feature. The operational pattern of the Hamm-Uentrop Combined-Cycle Power Plant presented in Reference [1] showed already at POWER-GEN Europe 2014 that severe load ramps for frequency support became a normal part of plant
operation. That paper presented the success in increasing the marketable secondary frequency support from 60 to 135 MW. The average load gradient during these 5-minute ramps was 27 MW/min.

Plant modernization efforts to increase load gradients have become more common in recent years, and in 2016 the load gradients of a combined-cycle power plant in southern Europe was raised to 50 MW/min, as shown for a load reduction case in Figure 2. This plant, equipped with two Siemens SGT5-4000F gas turbines, one SST5-5000 steam turbine and three SGen5-1000A electrical generators, was modernized by implementing several Flex-Power Services™ solutions to improve daily cycling capabilities which will be presented in the next section of this paper.

Figure 2: 50 MW/min power decrease of a Siemens SGT5-4000F gas turbine
3 Daily cycling solutions

Plants originally designed for base-load production but now operating in daily cycling mode, typically on line during the daytime and shut down at night for several hours, can benefit substantially from flexibility upgrades focused on hot startup and the shutdown processes.

3.1 Successful implementation of startup and shutdown improvements

The CCPP in southern Europe previously noted for its 50-MW/min load gradients gained remarkable improvement during startup and shutdown in terms of time-savings and gas consumption (Figure 3), leading to lower emissions as well. Startup time was reduced by 46 minutes – a 60% drop – while shutdown was cut by 17 minutes – 56% faster – for having implemented the changes in the unit control system.

![Figure 3: Cycling operation with and without startup and shutdown improvements](image)

Several products contributed to this plant’s impressive startup and shutdown time reductions of more than 50% each:
• Hot Start on the Fly
• Fast Plant Shutdown, and
• Load Gradient Optimization.

The most effective solution is a fully integrated start of the gas turbine and steam turbine called “Hot Start on the Fly”, illustrated here in a simplified graphics in Figure 4. For a plant configuration with one gas turbine and one steam turbine, a number of related services have already been implemented in the past, including those at Mainz-Wiesbaden CCPP in Germany which were presented at POWER-GEN Europe 2015 [2]. While the plant modernization displayed in Figure 3 was the first service action of this sort implemented in a 2x1 CCPP configuration, the technology is nevertheless the same as in single-shaft or other 1x1 CCPP configurations.

The “Fast Plant Shutdown” solution is based on a concept similar to that of “Hot Start on the Fly”: Long periods of gas turbine shutdown at the inlet guide vane (IGV) corner point are avoided in both cases, and both the gas and steam turbines start and stop in parallel in an integrated manner, fully automated by the unit control system.

Especially the reduction of the shutdown time displayed in Figure 3 has a contribution of the “Load Gradient Optimization” when ramping down in the IGV range, as described above in Section 2.

3.2 Further improvement potential

Development efforts aimed at enhancing plant flexibility are continuously ongoing, as the ultimate goal is a “switch on / switch off power plant” to achieve the fastest possible response to grid demand.

On top of the successes presented in Section 3.1, the Flex-Power Services™ portfolio features further improvements that will be implemented at another CCPP in Europe in 2017. The planned gas turbine modernization in this case includes implementing improved hardware in synergy with the regular overhaul scope for that plant, similar to the concept shown in Reference [3]. However, significant improvements in flexibility can be achieved with mostly software and minor hardware changes, as it was shown in Reference [4].

For the gas turbine as well as the steam turbine, load gradients during startup and shutdown may be increased by at least a factor of two, which is expected to further reduce cycling times in combination with the “Fast Plant Shutdown” and “Hot Start on the Fly” solutions. The latter is available in an advanced version as well that starts with a special sequence of the
various steam pressure levels (Hot Start on the Fly 2.0). An additional time benefit of up to 4 minutes was measured in testing at Mainz-Wiesbaden CCPP [2]. However, total values always depend on the specific plant configuration.

![Diagram showing Hot Start on the Fly and further improvement potential](image)

**Figure 4: Hot Start on the Fly and further improvement potential**

In addition to the load gradient increases of the steam turbine, the standard speed gradient during startup may be doubled as well, relative to the standard settings used in the past, by implementing the “Advanced Fast Loading” concept.

### 4 Intermittent operating solutions

As presented in *Section 3*, excellent solutions are available for daily cycling, which is an appropriate operating mode when negative clean spark spreads prevail at night and positive spreads occur during the daytime, as was the case on most business days in the months shown in *Figure 5*. Green cells represent hours with a positive clean spark spread, meaning the electricity price is equal to or exceeds variable CCPP generation costs. The diagram consists of 24 columns which, from left to right, show the hours from 1:00 AM around the clock to midnight. December 1 is shown at the top of the vertical axis, with January 31 at the bottom.
of the diagram. The sample efficiency level used to evaluate the clean spark spread was taken from a typical F-Class CCPP. The yellow and red cells depict a spread of less than €0.00/MWh, and -€3.00/MWh. Similar diagrams which compare the years from 2010 to 2014 are presented in Reference [2], revealing the reason for the decreasing number of operating hours at most CCPPs in Germany and the resultant change in the operational profile of these plants.

![Figure 5: Hourly clean spark spreads for n F-Class CCPPs in Germany, Dec 2016 and Jan 2017](image)

It is obvious that operation on and after Christmas 2016, when most factories were on hold, was not attractive at all for a CCPP (marked in Figure 5 with a blue frame). Just a few days later, however, market conditions were appropriate to start the plants and the question is how long it takes until a plant can generate power when an attractive spread occurs in the market. This is why efforts have been made to add solutions for improved starts after stops of several days to the Flex-Power Services™ portfolio.

### 4.1 Cold start with variable IGV operation

Under particular market or weather conditions, periods lasting up to several days or even weeks can go by without request for operation of the CCPP. Solutions are therefore required that reduce the commercial hurdles of cold startup, which include long startup times as well as high startup costs due to increased fuel consumption at low efficiencies as well as increased service-life consumption of steam-cycle components.

Although cold startup time and increased service-life consumption are mostly related to steam plant components, modifications to gas turbine operation logics can help to improve the situation.
As illustrated in Figure 6, exhaust gas temperature gradients of gas turbines shown as corrected outlet temperature (OTC) are high during loading after synchronization because the load is increased at a constantly low mass flow. The mass flow is increased after reaching the temperature setpoint for inlet guide vane (IGV) operation. While this mode of operation is usually desirable for hot starts when steam plant components are still at elevated temperatures, at cold starts these conditions induce high thermal stresses unless the gas turbine load gradient is reduced.

![Figure 6: Standard cold startup scenario for CCPPs; IGV= inlet guide vane position, OTC= corrected outlet temperature](image)

It’s possible to significantly reduce the stress related to the gas turbine exhaust temperature gradient by varying the gas turbine mass flow during loading after synchronization before reaching the standard temperature setpoint for IGV operation. This is shown in Figure 7. In principle, the boundaries for such variation are, on the one hand, the standard load curve with increasing temperatures at constant mass flow, and loading at constant exhaust temperature by increasing the mass flow after synchronization on the other. The actual operating conditions needed to effectively reduce stress at the heat recovery steam generator and throughout the overall plant lie between these boundaries, depending on the temperature level at the specific components.
Testing has been conducted at an SGT5-4000F service plant for the purpose of validating combustion stability at varying mass flows during loading after synchronization.

The primary focus of this testing was to validate the curve denoted “Variable IGV operation” in Figure 7 in order to reduce time to steam production at parameters required for district heating. While the operational concept for initial loading was altered, the acceleration,
ignition and synchronization procedures were left unchanged. The actual test curves for this operational curve are shown in Figure 8. Combustion stability proved to be robust for the illustrated test on this service engine. The present combustion system equipped with an SGT5-4000F-specific annular combustor with ceramic tiles was able to handle the modifications to the operating line without notable impact on the relevant monitoring parameters.

![Fatigue per cycle for HP super heater header](image)

**Figure 9: Impact of mass flow variation during initial gas turbine loading on cyclic life of high-pressure superheater header**

The predicted impact on the boiler was evaluated based on finite element analysis considering the actual test case in which boiler operation was partially under manual control. A simulated case in which optimized automated control of the boiler was assumed has also been analyzed. Figure 9 shows the impact of variable mass flow operation of the gas turbine on one example component of the HRSG, the high-pressure super heater header. According to the analysis results, cyclic service-life consumption of this boiler component can be reduced by 25% by adjusting the IGV schedule of the gas turbine to the variable IGV operating line depicted in Figure 7. Additional potential is seen in also reducing the exhaust temperature gradient of the gas turbine with maximum mass flow of the GT applied starting from synchronization and accounting for a constant load gradient.
By changing the operating curve of the gas turbine, its components are affected differently by thermal stresses during initial loading. While hot-gas-path component stresses are reduced with the higher mass flow applied according to the lower exhaust gas temperature gradients, cold component stresses might increase due to the compressor pressure ratio building up faster in line with compressor exit temperature. However, temperature gradients applied to compressor, rotor and casing components for variable IGV operation with a 13 MW/min standard load gradient are still well below the approved startup gradient optimization with 30 MW/min. Consequently, it can be concluded that the current design of the SGT5-4000F can cope with the operating line introduced.

4.2 Steam Turbine Hot Standby

In addition to HRSG service-life consumption, the steam turbine startup requirements play a major role in determining startup times after long periods of plant shutdown. In Reference [2], the “Degassed Conductivity Measurement” was introduced as an effective means of steam quality measurement as well as an innovative concept for heating up the steam turbine rotor with LP steam from an external steam source. Another solution for heating up the steam turbine rotor is “Steam Turbine Hot Standby” (see Figure 9 and Figure 10). Contrary to the concept presented in Reference [2], this solution doesn’t need an external steam source, as the heat is generated by heating blankets. This equipment has been applied to steam turbines for many years, e.g. to reduce thermal stresses in thick-walled components. Design calculations and additional testing have proven another functionality of heating blankets: heating the steam turbine rotor by applying the blankets to the outer casing as shown in Figure 9. With a certain period of time, the heat is transferred via the inner casing to the rotor (see Figure 10).
The first implementation of heating blankets in a single-shaft unit to improve startup behavior of an F-Class CCPP in Europe is set to be tested later in 2017. At this plant, the application of heating blankets called “ST Hot Standby” will be combined with additional concepts for the steam cycle as well to create a total plant solution called “Go Ready”.

Figure 9: Steam turbine rotor in heated condition to reduce startup times

Figure 10: Temperature effect of heating blankets on the turbine components
5 Summary and outlook

Many solutions are available which allow flexible operation of fossil fuel power plants, some of which have been successfully applied for years already, while other, newer options are ready to implement now, and additional measures are being developed to grow the Flex-Power Services™ portfolio.

The solutions presented in this paper are linked to different operational situations as summarized in Figure 11:

1. Load Gradient Optimization
2. Hot Start On The Fly
3. Fast Plant Shutdown
4. Start Gradient Optimization
5. Hot Start On The Fly 2.0
6. Advanced Fast Loading
7. Cold Start with Variable IGV Operation
8. Steam Turbine Hot Standby

![Figure 11: Summary of solutions to improve plant operational flexibility](image)

Commercial verification for implementing flexibility solutions strongly depends on the plant-specific environment and local market conditions.

It is important to watch developments in the market and anticipate attractive market conditions as were found in January 2017 in Germany. A few “golden hours” occurred with clean spark spreads above €100/MWh, shown in Figure 12 in yellow and marked with a blue frame. If plant operators wish to harvest only best spreads and avoid uneconomical hours, solutions are needed which enable plants to be ready for pinpoint operation: in extreme cases,
“binary power generation” as a “switch on / switch off plant” may be best suited to fulfilling grid demands. Excellent weather conditions and market forecasting, full plant automation and flexible maintenance concepts to shift service events to times of negative clean spark spreads are all aspects which have to be considered and addressed on the road to achieving these objectives.

![Figure 12: Clean spark spread hours in Germany higher than €100/MWh marked in yellow](image)

6 Conclusions

Germany’s Energiewende (known as the “energy turnaround” or “energy transition”) and the related changes to power plant operation to compensate for the fluctuating and intermittent nature of renewable power generation have been the subject of debate in the European power industry for years. Many countries around the world are experiencing similar changes already, or are pursuing decarbonization of their power sector and will reach the need for more flexible fossil fuel plants in coming years. Siemens is continuously expanding its Flex-Power Services™ portfolio of plant solutions designed for implementation in fossil-fired plants to enhance their capabilities of partnering up with renewable energy sources. Whether or not the business case of a power plant is viable for implementing these features strongly depends on local market conditions. Examples of new product developments and successful plant implementation have been presented in this paper.
7 References


8 Disclaimer

These documents contain forward-looking statements and information – that is, statements related to future, not past, events. These statements may be identified either orally or in writing by words as “expects”, “anticipates”, “intends”, “plans”, “believes”, “seeks”, “estimates”, “will” or words of similar meaning. Such statements are based on our current expectations and certain assumptions, and are, therefore, subject to certain risks and uncertainties. A variety of factors, many of which are beyond Siemens’ control, affect its operations, performance, business strategy and results and could cause the actual results, performance or achievements of Siemens worldwide to be materially different from any future results, performance or achievements that may be expressed or implied by such forward-looking statements. For us, particular uncertainties arise, among others, from changes in general economic and business conditions, changes in currency exchange rates and interest rates, introduction of competing products or technologies by other companies, lack of acceptance of new products or services by customers targeted by Siemens worldwide, changes in business strategy and various other factors. More detailed information about certain of these factors is contained in Siemens’ filings with the SEC, which are available on the Siemens website, www.siemens.com and on the SEC’s website, www.sec.gov. Should one or more of these risks or uncertainties materialize, or should underlying assumptions prove incorrect, actual results may vary materially from those described in the relevant forward-looking statement as anticipated, believed, estimated, expected, intended, planned or projected. Siemens does not intend or assume any obligation to update or revise these forward-looking statements in light of developments which differ from those anticipated. Trademarks mentioned in these documents are the property of Siemens AG, its affiliates or their respective owners.