Integrated Technologies that Enhance Power Plant Operating Flexibility

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Abstract

The US electric power industry has changed dramatically since the downturn of the gas-turbine-based market in the early 2000's. In the years prior to this, nearly all combined-cycle plants were planned, permitted and built with the expectation to be operated predominantly in base load. With the addition of excess generating capacity in the industry coupled with rising natural gas prices, many of the new plants had to address a new set of challenges posed by nightly and weekend shutdowns and subsequent fast start-up requirements to remain economically viable.

These same challenges will be imposed on new natural gas-fired units in the foreseeable future. To enhance the value of the new power generation assets, the US market will require these new power plants to provide a much higher level of operating flexibility, including the following needs:

- Built to span from continuous- to intermediate-duty operation
- High efficiency to maximize generation opportunities
- Rapid start to react to market opportunities
- Lower start-up emissions
- Lower operating costs (high start efficiency)
- Lower demineralized water consumption

Siemens has developed highly integrated power plant solutions that offer reliable rapid start and cycling flexibility without compromising efficiency. This paper discusses proven technologies that have been integrated to permit F-class gas turbines in combined-cycle plants to be brought to 150 MW load in as short as 10 minutes and bottoming cycles that can be brought to full load in less than half the times of their predecessors. It will also address results of testing in operating power plants that incorporate these integrated components and systems.

Introduction

Development of the gas-turbine based market in the U.S. illustrates the classic boom-bust cycle in the electric power generation industry. As shown in ***Figure 1***, the Public Utilities Regulation Policy Act (PURPA) passed in late 1978 consequently led to a small

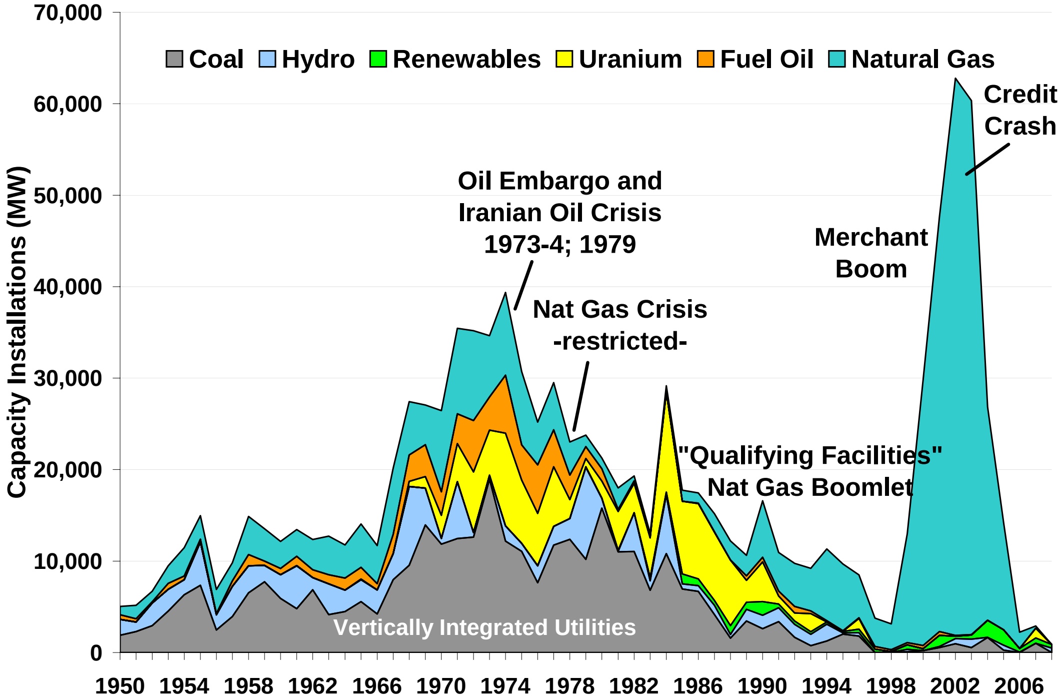

Figure 1: US Electric Power Generation Capacity Additions (Source: EIA)

boom of natural gas-fired generation capacity additions from the mid-1980's through the mid-1990's. During this 10-year period, gas-turbine based additions accounted for roughly half of the total power generation installed in the U.S. During the same time period however, total power generation additions significantly dropped to a fraction of the historical level of 20 to 30 GW per annum. This trend bottomed in 1998, when only 3 GW of total capacity were added (only 0.8 GW of which was gas-turbine based).

This prolonged lull in building power generation set the stage for what occurred from 1999 through 2005, when more than 200 GW of gas-turbine-based capacity were added. Low reserve margins caused widespread concern in numerous areas throughout the U.S. to add generation as quickly as possible. With natural gas pricing of approx. $2 per mm BTU during the timeframe that this capacity was being planned and ordered, gas-turbine based technology best satisfied this need, as either simple-cycle or combined-cycle power plants.

Figure 2 shows gas-turbine-based capacity additions in the U.S. since 1998 [1]. There is a good mix of simple-cycle and combined-cycle applications with a shift toward the latter in the later years of the boom, which to some degree reflects project lead time differences between the two applications. Implicit in the chart is the traditional application of simple-cycle units for peaking/cycling duty and combined-cycle units for base-load/continuous operation duty.

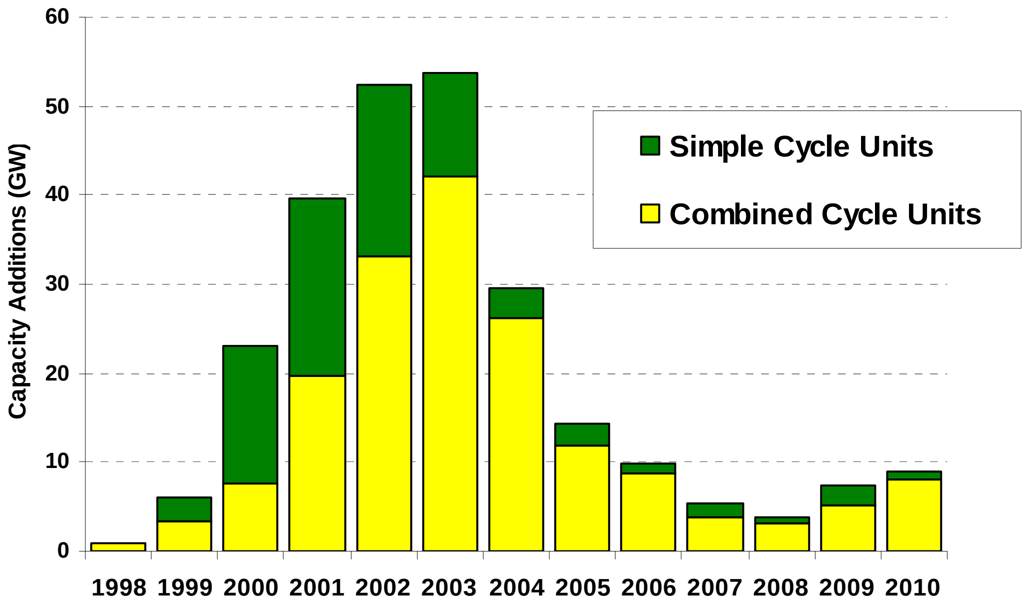

Figure 2: U.S. Gas-Turbine-Based Capacity Additions
(Source: Combined Cycle Journal First Quarter 2007)

With the sharp increase of natural gas prices to $5- $8 per mm BTU in 2004, owners and operators of gas-turbine-based generation needed to revaluate their fleet to optimize the utilization of these assets. As evidenced by a recent analysis conducted by Strategic Power Systems [2], there has been noticeable change in service hours/start for F-class gas turbine units in base-load/continuous duty (i.e combined-cycle applications) from the 5-year time period of 1997 to 2001 to that from 2002 to 2006. The trend has been toward a significantly lower average from 108 to just under 59 service hours/start. At the same time, the average service factor (service hours/period hours) for these units decreased only 1.5% from 64.5% to just under 63%. This signifies that on-average the F-class combined-cycle fleet is presently being shut down and started almost twice as often as before. The implication is that many F-class plants are now being started on a daily basis.

Also shown in this analysis is that the service factors for the F-class gas turbines in standby/peaking duty (i.e. simple-cycle applications) dramatically decreased during the same 5-year periods from 13.5% to just over 4%. The reason for this is most likely a combination of the following:

1. simple-cycle efficiencies of even the F-class units may not high enough for them to be dispatched
2. start-up times for the F-class gas turbines may not be fast enough to meet system demands
3. start-up fuel costs may be prohibitively high

4. maintenance costs for start-up may be too high

These dramatic shifts in operating parameters point to a growing need in the U.S. power generation industry for higher flexibility from its F-class gas-turbine-based applications. This flexibility must allow them to cost-effectively dispatch their peaking (now characterized by simple-cycle) units for more hours and to start their base-load (combined-cycle) units more frequently and effectively. To help the industry maximize its profits from new generating assets, suppliers must address these requirements for operating flexibility as the U.S. market for gas-turbine-based units begins to rebound in the future (refer to ***Figure 2***), with almost 6 GW of orders in 2006 and over 30 GW to be installed by 2012. As referenced in this article, this does not take into consideration the number of new coal-fired plant cancellations and permitting delays, that will lead to capacity shortfalls, which will most likely be filled by addition of "still more GT-based capacity".

Power Plant Design Integration

Siemens is not only an original equipment manufacturer (OEM) of gas turbine-generators, steam turbine generators and many of the plant components and systems, but also the supplier for some 520 combined cycle power plants (130 on a turnkey basis) and the operation and maintenance (O&M) provider for 40 power plants. As a result, we have the in-depth knowledge and in-house expertise to implement highly integrated gas-turbine-based power plant designs. We also understand that the recent changes in operating requirements throughout the industry for increased flexibility have brought new challenges to the traditional simple cycle and combined cycle technologies presently in service. This has placed an even higher importance on an integrated plant design.

Figure 3 shows the elements of combined cycle plant design integration that are impacted by the new market demands. All of the elements shown play a key role in the start-up capability of the plant, and an in-depth knowledge of each and the inter-relationships between them is essential.

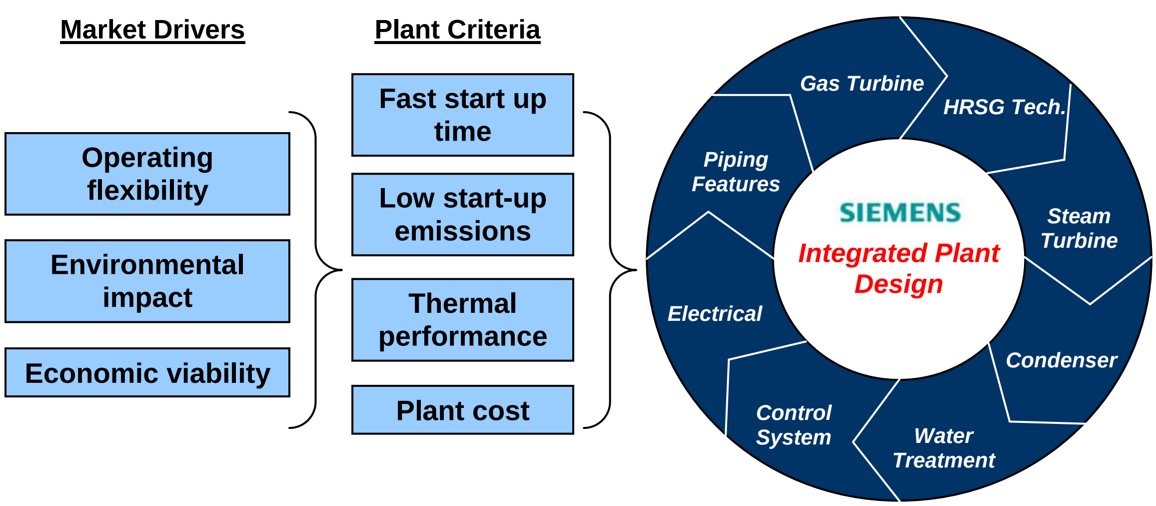

Figure 3: Integrated Plant Design to Meet Market Demands

At the core of the technology, the gas turbine forms the bases for operating parameters and limits of the combined cycle plant. Recent advances in the design of the Siemens SGT6-5000F gas turbine-generator package have enabled improvements in overall plant flexibility. This includes the development of an ultra low NO_x (ULN) combustor with reduced emissions of 9 ppm dry and low-load CO reduction hardware. It also includes advancements in the package to start the gas turbine more quickly to reach emissions compliance earlier and significantly reduce overall start-up emissions. In fact, the SGT6-5000F package with static frequency converter (SFC) start is the only frame gas turbine that can qualify for 10-minute non-spinning reserve by utilizing the SGT6-5000F capability of attaining 150 MW in 10 minutes without imposing a maintenance impact for the start. This will be addressed in further detail later in the paper.

To capitalize on this fast starting capability of the gas turbine, the bottoming cycle of the plant must be skillfully designed to address and alleviate component and system limitations. The heat recovery steam generator (HRSG) must be designed with features to accommodate the high temperature exhaust gas flow during rapid start-up of the gas turbine. Operating experience in the industry with F-class combined cycle plants has shown that the traditional triple-pressure reheat drum-type HRSG with steam pressures in excess of 2000 psi are not well suited for this operating regime, especially longer term operation in a daily-start mode.

There are two primary concerns that need to be addressed in HRSG design for fast start:

1. component failure
    a. high steam conditions require thick component walls
    b. fast start-up results in high thermal gradients in the walls
    c. components fail after fatigue life is consumed
2. drum level control
    a. gas turbine start-up produces rapid boiling in the evaporator
    b. if water level in the drum rises to the separators, water carry-over into the superheater may occur
    c. the typical response to this is to either trip or slow the gas turbine load ramp

There are two fast-start HRSG designs that the authors' company have adopted for its combined cycle plant portfolio. The first is the BENSON® once-through HRSG, which replaces the thick-walled high pressure (HP) drum with external steam separators and a surge bottle. This type of HRSG is especially suited for triple-pressure reheat F-class combined cycle applications. The BENSON® once-through HRSG was successfully applied to an F-class gas turbine plant in 1999, when the 390 MW Cottam combined cycle plant in Great Britain went into operation. Since then, an additional dozen 400-800 MW combined cycle plants using BENSON® HRSG technology have been ordered, several of which will go into operation later this year. Almost all of these plants are being implemented on a turnkey basis by Siemens.

The second HRSG design is a modified drum design, which has similar characteristics to the once-through design. This design reduces the diameter of the drum, which functions as primary steam separation and water inventory. Secondary steam separation is accomplished external to the drum. The authors' company has integrated this HRSG design into one of its combined cycle F-class fast-start products, which incorporates a simplified single-pressure bottoming cycle with reduced steam conditions, which will be discussed in more detail later.

Steam produced in the bottoming cycle from the HRSG is then admitted to the steam turbine. As an OEM of steam turbine generators, condensers and plant control systems, Siemens has developed an advanced integrated bottoming cycle design utilizing steam bypass systems and steam conditioning, along with the patented steam turbine stress controller (TSC) and the SPPA-T3000 control system to optimize plant start-up.

Leveraging its OEM expertise and combined cycle integration know how, Siemens has continued to invest in the further development of its SCC6-5000F Series combined cycle product portfolio with fast-start capability to address the industry's need for improved operating flexibility with minimized environmental impact. This series of products is the Siemens Flex-Plant™ portfolio. Two of the 60 Hz products in this portfolio will be addressed further in the paper:

- SCC6-5000F 2x1 Flex-Plant™ 30, a highly efficient (57+% net) 590 MW plant, which can be started up in half the time of traditional F-class plants.
- SCC6-5000F 1x1 Flex-Plant™ 10, a 275 MW plant with 48% net efficiency, which can generate 150 MW within 10 minutes.

SCC6-5000F 2x1 Flex-Plant™ 30- Expanded Economic Dispatch from Continuous- to Intermediate-Duty Operation

With the surge in natural gas prices in the early 2000's, it became increasingly apparent that future F-class combined cycle plants would be subjected to more frequent start-ups and cycling. At the same time, the higher gas prices also dictated that plant efficiencies not be compromised. With this as the backdrop, the authors' company launched a program in 2002 to integrate fast-start technology into its existing highly efficient 2-on-1 60 Hz F-class combined cycle product with a triple-pressure reheat bottoming cycle. The focus of the program was to take a product designed primarily for continuous-duty operation and expand its flexibility to span continuous- to intermediate duty operating regimes in an economical manner.

Reviews of existing F-class combined cycle units showed that plants designed for continuous-duty operation had excessive start times due to equipment restrictions. To reduce start-up times, the following challenges were addressed:

- HRSG ramp capability
- Steam turbine ramp capability

- Piping warm up times
- Steam chemistry
- Steam turbine back-pressure limitations

Collaborative work globally within a special task force with the charter to develop a fast-cycling combined cycle plant led to the integrated fast-start technology [3] used in the SCC6-5000F 2x1 Flex-Plant™ 30- hereafter referred to as the Flex-Plant™ 30. A prerequisite to the team was the use of existing technologies with proven, reliable operational experience. Of note is that this integrated package was used in the development of a complete portfolio of 50 and 60 Hz F-class combined cycle fast-start plants.

Figure 4 shows the components and systems that make up the integrated fast-start technology package. For ease of display, a single-shaft combined cycle plant is shown. The same features are used for the Flex-Plant™ 30, including:

- Triple-pressure reheat HRSG with BENSON® once-through technology
- High-capacity steam attemperation and full-capacity steam bypass systems
- Innovative piping warm-up strategies
- Siemens' steam turbine stress controller (TSC)
- Modern water treatment system with condensate polishing
- Optimized plant standby using an auxiliary boiler to maintain vacuum

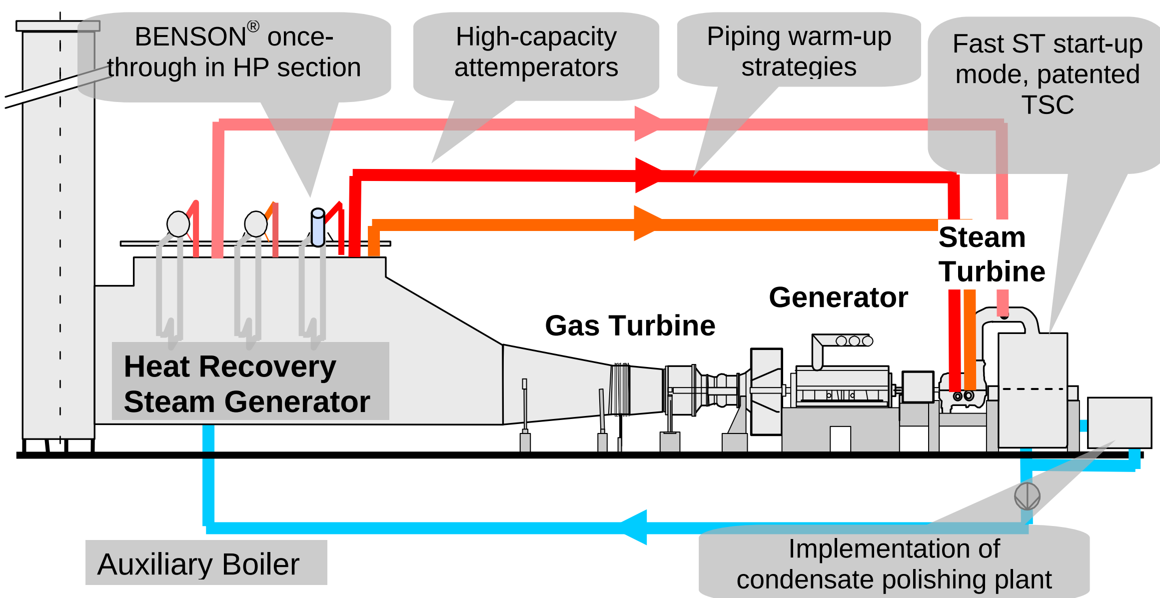

Figure 4: Integrated Proven Fast-Start Technology Package for Flex-Plant™ 30

As already mentioned in the previous section, the BENSON® once-through HRSG (depicted in ***Figure 5***) has demonstrated that it is ideally suited to handle fast start-ups.

The Cottam unit achieved its 1000th successful start and clocked 60,000 fired hours on November 5, 2006. The water treatment system used with this type of HRSG design incorporates a condensate polishing system, which together with an auxiliary boiler has eliminated holds in plant start-up required to meet steam/water cycle purity [4].

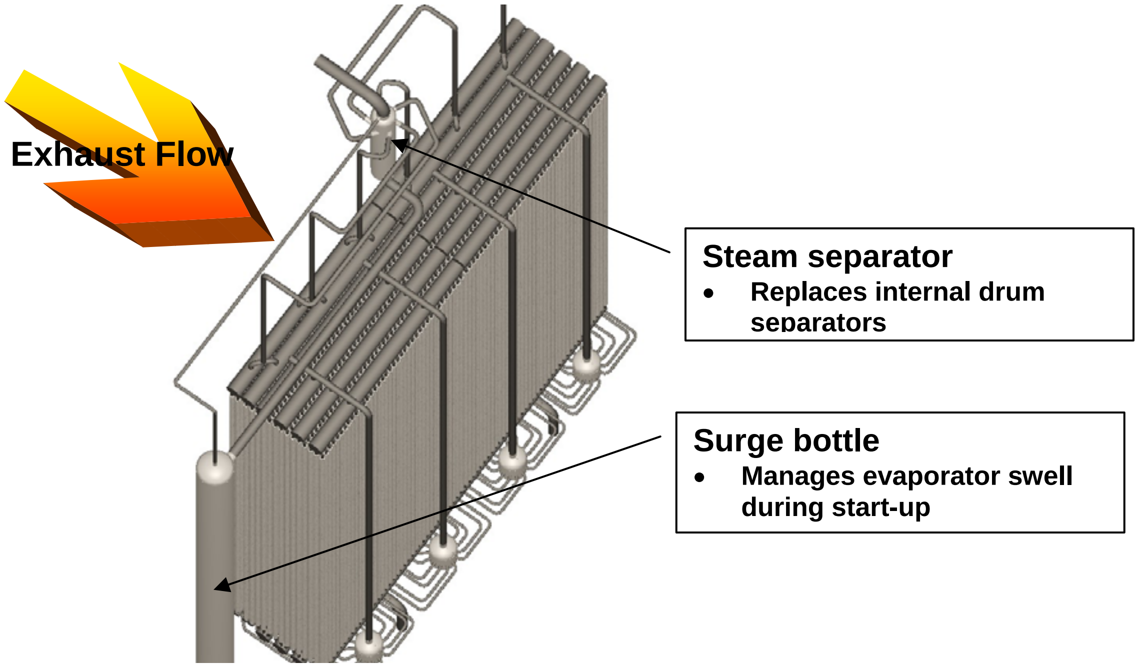

Figure 5: BENSON® Once-Through HRSG Design

The application of proven steam conditioning and pipe warming techniques and full-capacity steam turbine bypass systems, together with the use of the Siemens steam turbine stress controller (TSC) enables rapid start-up of the plant. The TSC provides the option to select the steam turbine ramp rate, and the associated expended fatigue life is calculated and the remaining life expectancy is shown. This allows the plant operator to take advantage of lucrative fast dispatch situations thereby increasing the value of the asset.

The integration of these fast-start features has resulted in significantly reduced plant start-up times. As shown in ***Figure 6***, hot starts after overnight shutdowns have been achieved in less than half the time required for standard combined-cycle F-class plants. Additional development and testing has been conducted by Siemens to further reduce start-up times. Through further integration of the plant control system and balance of plant design, steam is admitted into the steam turbine as it is produced in the HRSG. This mode of operation was retrofitted and tested in May of 2005 in an operating 400 MW combined cycle power plant with a drum-type HRSG. ***Figure 7*** shows that full load was achieved in less than 40 minutes after an 8-hour shutdown [5]. The Siemens SPPA-T3000 control system offers an ideal platform for the plant dedicated control system (DCS) to facilitate such simplified fast-start capability. Based on plant test results, the application of this mode of operation to Flex-Plant™ 30 should reduce start-up times by another 10-15 minutes, allowing it to achieve the fastest start-up time of any combined cycle plant. Just as important, the gas turbines in Flex-Plant™ 30 are quickly ramped to emissions compliance load within 20–25 minutes, compared to an hour and a half for the standard plant.

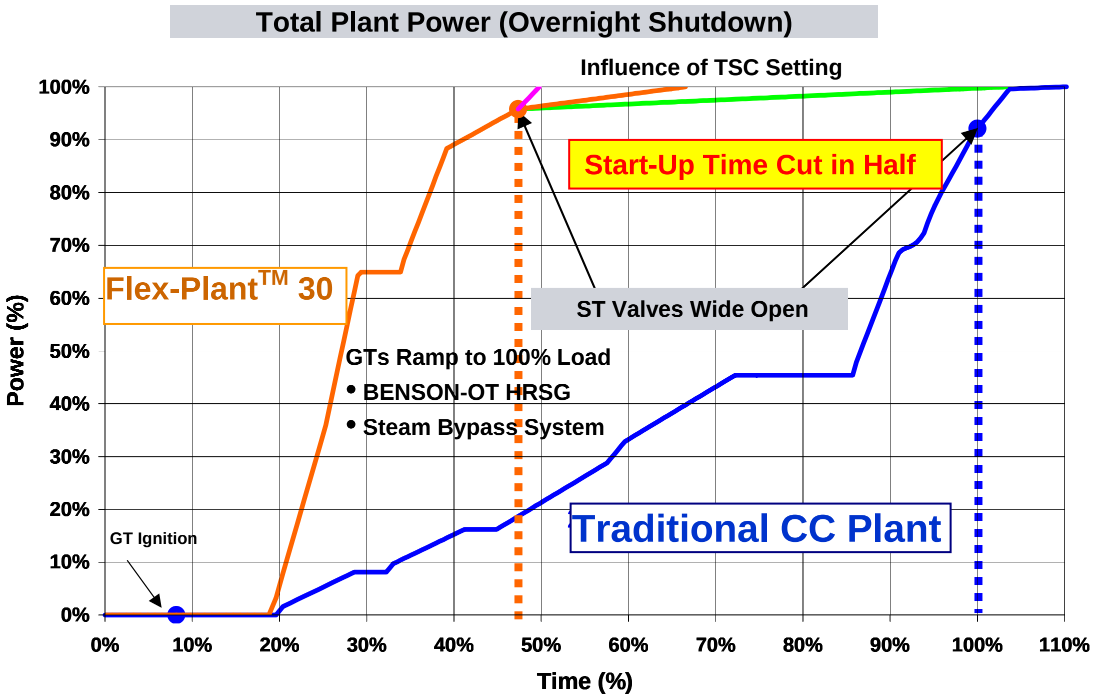

Figure 6: Comparison of Plant Loading Profiles for Fast-Start and Standard 2-on-1 F-Class Combined Cycle Plants

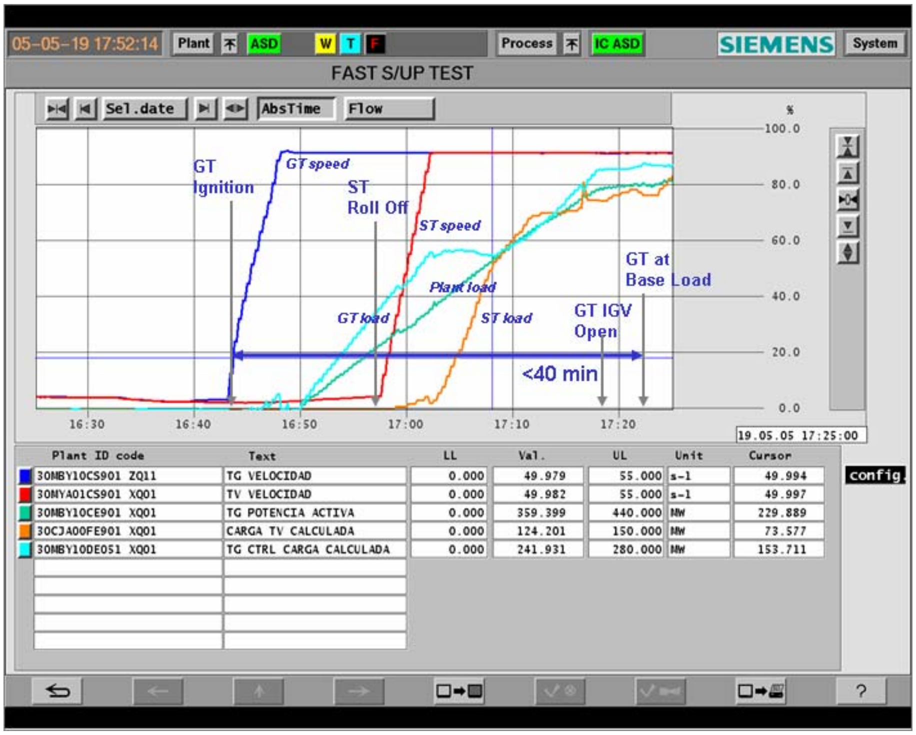

Figure 7: Hot Start of a 400 MW Combined Cycle Plant Retrofitted with Optimized Steam Turbine Start-Up Technology

With these reduced start-up times, Flex-Plant™ 30 provides the benefit of not only more dispatchable power more quickly, but is designed to significantly reduce start-up emissions and start-up fuel costs. Using the plant design basis of 250 starts/stops to reflect the industry need for overnight and weekend shutdowns, this amounts to a potential annual reduction of more than 300 tons of CO, 75 tons of NO_x and 30 tons of VOC. Over a projected 20-year life basis, the Flex-Plant™ 30 is predicted to emit 6,000 tons less of CO and 8,000 tons less of total pollutants. At the same time, this plant is designed to utilize less start-up fuel, which could amount to fuel cost savings in the order of millions of dollars annually.

With its inherent proven fast-start technology the SCC6-5000F 2x1 Flex-Plant™ 30 provides the ideal solution to span continuous to intermediate-duty dispatch requirements. This 590 MW combined cycle plant provides operating flexibility without compromising high efficiency. By reducing start-up time, it provides more power to the grid much sooner and it greatly reduces emissions and start-up fuel consumption. All these attributes should make it a highly valuable asset in the power generation market, and one that should be easier to permit especially under the ever more restricted environmental pressures that will be placed on the industry.

SCC6-5000F 1x1 Flex-Plant™ 10- Expanded Economic Dispatch from Peaking to Intermediate-Load Operation

There has been a renewed interest in peaking and intermediate load operating regimes during the past two years. The demand for ancillary services support, predominantly for

10-minute non-spinning reserve, has also become more acute. And the environmental pressures on emissions and water usage continue to grow.

Siemens' 198 MW SGT6-5000F with the fast-start package is the only industrial frame gas turbine-generator that has been demonstrated to generate 150 MW in as little as 10 minutes (and reach full load in 12 minutes) without imposing additional start-related maintenance impacts. With its high F-class simple cycle net efficiency of over 38%, it is ideally suited for peak load applications. However, as the demand has grown to operate for more hours (from 500 hours to 2000-3000 hours per year), this efficiency at today's high gas prices becomes more limiting. And at the same time, the high capital costs and complexities of traditional combined cycle plants make them less suitable for this operational mode.

After careful analysis of the industry's needs using quality function deployment (QFD), the authors' company looked at its proven fast-start technologies base and developed a uniquely integrated plant solution that leverages the 10-minute start capability of its SGT6-5000F gas turbine with the higher efficiencies of a simplified bottoming cycle. Goals for the product were set as follows:

- Retain the 10 minute gas turbine start capability
- Minimize emissions using proven technologies
- Minimize water consumption
- Maximize plant efficiency with minimized plant complexity

The 275 MW SCC6-5000F 1x1 Flex-Plant™ 10 plant (hereafter called Flex-Plant™ 10) meets all of these goals. This combined cycle plant incorporates a simplified single-pressure bottoming cycle with reduced steam temperatures and pressures. Key features of the plant are as follows:

- Built around the SGT6-5000F with 10-minute start capability and 9 ppm NO_x dry ULN combustion system
- Advanced single-pressure non-reheat HRSG with conventional SCR
- Bedplate-mounted non-condensing steam turbine
- Air-cooled heat exchanger condenser with full-capacity steam bypass system
- Air-cooled generators for gas and steam turbines

Figure 8 depicts a graphic from the fully developed 3-D model of a two-unit Flex-Plant™ 10. Each unit is identical to the other. A common control building is shown in the foreground and a common gas conditioning skid and water tanks are shown in the background.

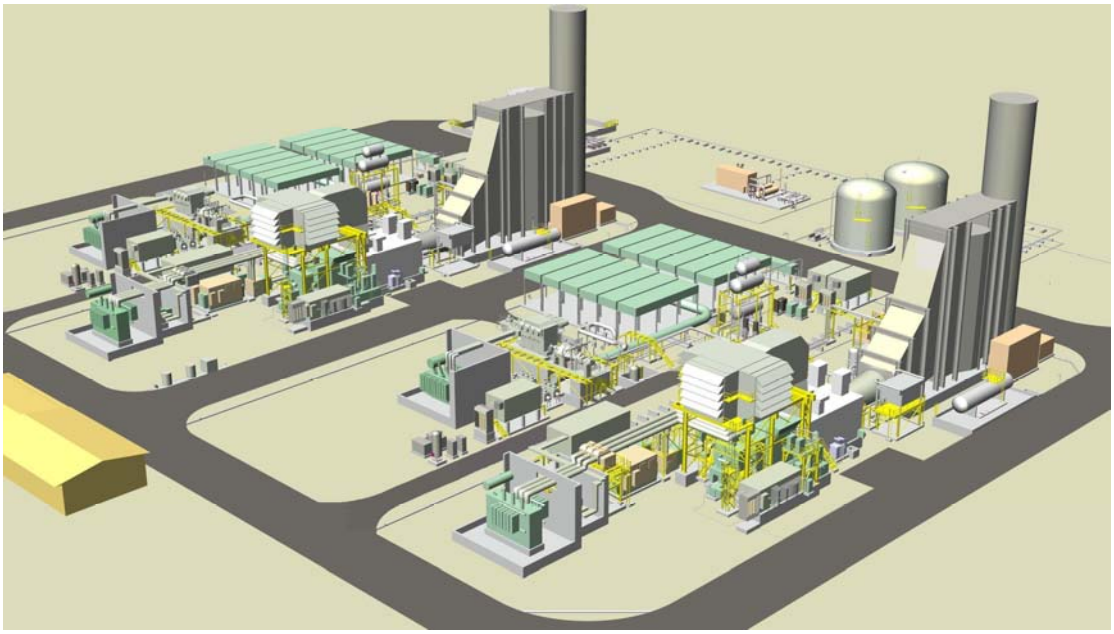

Figure 8: 3-D Model of Two-Unit SCC6-5000F 1x1 Flex-Plant™ 10

By leveraging its knowledge and expertise with the BENSON® once-through HRSG technology, the authors' company has worked closely with key HRSG suppliers in development of a modified drum-type design (discussed previously in the paper) that is well suited to handle fast start for the reduced steam operating pressures and temperatures used in the Flex-Plant™ 10. Extensive HRSG transient analysis work was completed as part of the overall lifetime analysis program to validate the design. The HRSG is designed with a conventional SCR, which together with a CO catalyst reduces plant emissions to best available control technology (BACT) levels.

The one-casing SST-800 steam turbine is of single-pressure non-reheat non-condensing design. It is shipped fully mounted on a bedplate to the jobsite for simplified installation. The air-cooled generator is also shipped to jobsite fully assembled. To minimize water usage, an air-cooled heat exchanger condenser is used.

A typical start-up of the Flex-Plant™ 10 after an overnight shutdown shows the advantages of the integrated plant design. By utilization of an SFC, the generator is motored to bring the gas turbine up to speed (without the typical over-firing of the gas turbine that is required by use of a starting motor) and the unit can generate 150 MW with NO_x emissions of 9 ppm dry in as little as 10 minutes. With the installation of SCR and CO catalysts, stack emissions compliance is reached in about 20 minutes. Steam that is produced in the HRSG is bypassed to the condenser until the steam turbine is ready to accept steam flow. Full combined cycle plant load is reached in about 45 minutes. Noteworthy is that the average start-up efficiency is almost 40%. Additional work is being done within Siemens to integrate additional fast-start features from the

Flex-Plant™ 30 to further reduce start-up times, which will not only increase the amount of dispatchable power earlier, but also further improve start-up efficiency.

Utilization of the fast-start gas turbine has additional advantages regarding CO, NO_x and VOC emissions. While the fast-start technology used in the Flex-Plant™ 30 already greatly reduces the start-up emissions from a traditional combined cycle triple-pressure reheat plant, the Flex-Plant™ 10 further cuts these already low emissions almost in half, to 152 lb/start for CO, 11 lb/start for NO_x and 13 lb/start for VOC.

Another important feature of the Flex-Plant™ 10 is that by adding evaporative cooling and steam power augmentation, the plant power output remains quite constant over the entire design ambient temperature range (refer to ***Figure 9***). The plant heat rate also is very flat over the ambient temperature range (***Figure 10***).

Operating parameters for the SCC6-5000F 1x1 Flex-Plant™10 are as follows:

	ISO (Dry)	ISO (Evap Cooler)	ISO (Steam Power Aug)
Net Output (MW)	255	260	275
Net Efficiency (%)	48.5	48.5	48.2
Water Usage (gpm)	14	40	300

SCR and CO catalyst for 2 ppmvd NO_x, 2 ppmvd CO and 1 ppmvd VOC

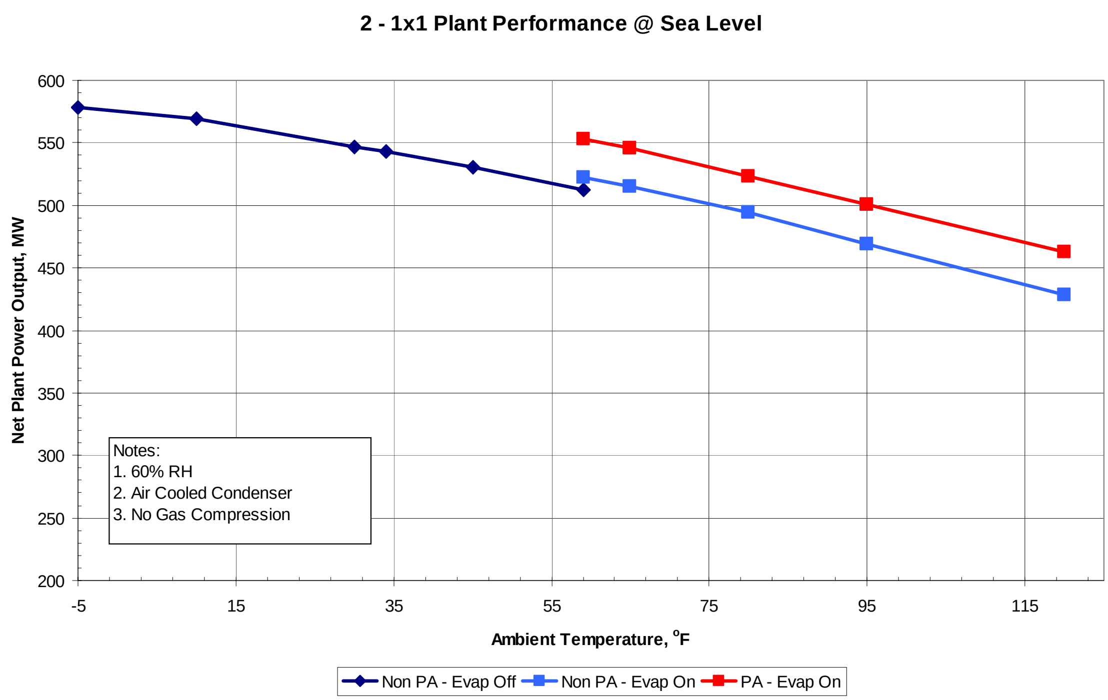

Figure 9: Net Plant Power vs. Ambient Temperature for Two-Unit SCC6-5000F 1x1 Flex-Plant™ 10

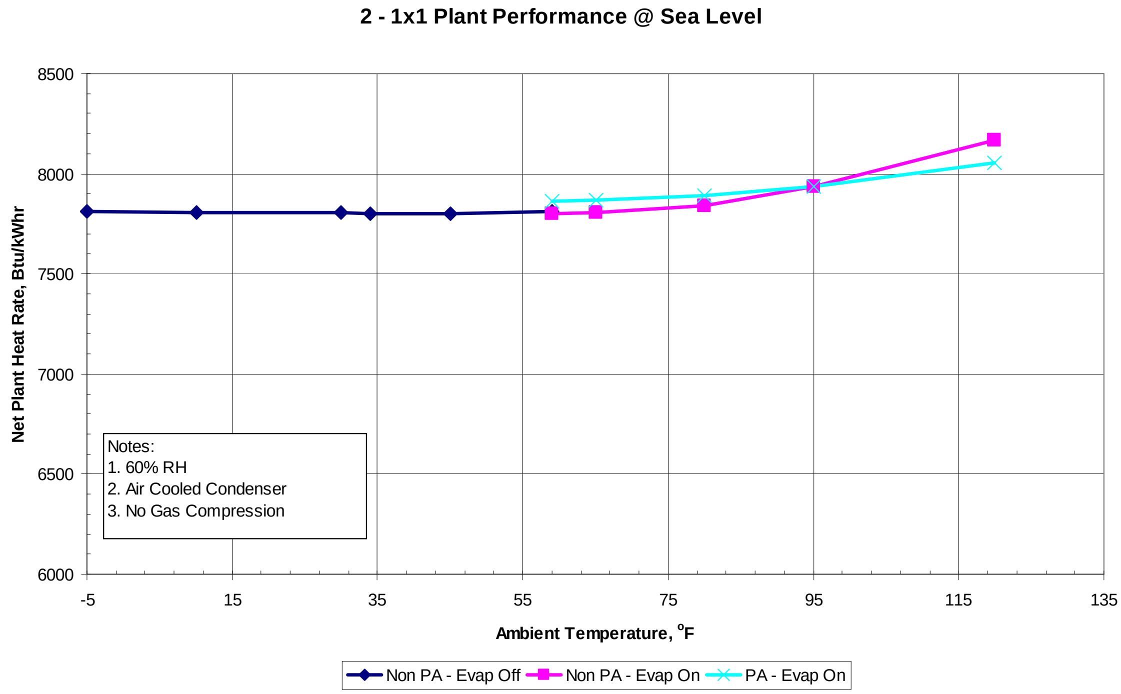

Figure 10: Net Plant Heat Rate vs. Ambient Temperature for Two-Unit SCC6-5000F 1x1 Flex-Plant™ 10

To cover their intermediate-load needs, power generation companies in the past have typically turned to aero-derivative gas turbine products that provide somewhat higher simple cycle efficiencies (nominally 41-42%), but these have traditionally been limited in size to 40-50-MW. A new engine has recently been introduced to the market with a nominal 100 MW rating that provides nominally higher efficiencies. The technology is an intercooled aero-derivative (ICAD) gas turbine that utilizes a relatively complex balance-of-plant package beyond that of simple-cycle gas turbines, including an intercooler, heat exchangers, and an array of large interconnecting piping. This product provides 10-minute start capability and relies on water injection to reach 25 ppm NO_x emissions. A hot selective catalytic converter is required for lower emissions.

The performance of Flex-Plant™ 10 compares quite favorably to the aero and ICAD products with:

- A net efficiency that is 6-7% points higher
- Fuel gas pressure requirements that are roughly half, which greatly reduces the auxiliary load required for gas compression

- NO_x emissions of 9 ppm dry from the SGT6-5000F, compared to 25 ppm with water injection
- Very low water usage

Another noteworthy item is plant operating reliability. In the article referenced previously [2], SPS data show a comparison of mean-time-between-unplanned-outages for aero-derivative and F-class gas turbines. Using the cycling operating regime (with 876 to 4380 service hours per annum), the chart shows that the F-class units operate almost four times longer between unplanned outages.

With its inherent non-spinning 10-minute-start capability to 150 MW and 30 MW/minute load regulation up or down, the SCC6-5000F 1x1 Flex-Plant™ 10 provides the ideal solution to span peaking to intermediate-load dispatch requirements. This 275 MW combined cycle plant provides considerably higher efficiencies than any frame or aero-derivative gas turbine simple cycle plant without compromising operating flexibility. With this fast-start technology, it provides more power to the grid much sooner and it greatly reduces emissions, water usage and start-up fuel consumption. All these attributes should make it a highly valuable asset in the power generation market, and one that should be considerably easier to permit especially under the ever more restricted environmental pressures that will be placed on the industry.

Conclusion

Today's US electric power generation requirements place new demands on gas-turbine-based technologies to provide more operating flexibility. These demands will become even greater in the future. With a growing uncertainty in the industry of future fuel prices and environmental pressures, it will become even more difficult to predict the dispatch requirements for new power generation assets. The availability of products that can more economically span wider ranges of operating regimes will become even more paramount to maximize the commercial value from these plants.

The authors' company provides a unique portfolio of gas-turbine-based products that offer unparallel operating flexibility. All of these products are built around the long proven Siemens' SGT6-5000F gas turbine, which has demonstrated unsurpassed reliability and availability in the F-class segment. With the introduction of 9 ppm dry ULN combustion, low CO turn-down and fast start, this 198 MW gas turbine is truly the best in its class. In simple cycle plant applications, this gas turbine can provide 150 MW of non-spinning 10-minute reserve power, cleanly and efficiently, without a maintenance impact of the start. As such, it is ideally suited for peaking load regimes.

As the operating requirements shift to more hours of operation toward intermediate duty, the 275 MW SCC6-5000F 1x1 Flex-Plant™ 10 becomes the product of choice with its increased efficiency without compromising the 10-minute non-spinning reserve capability. The Flex-Plant™ 10 is also the most environmentally friendly gas-turbine-based product on the market with minimized water consumption and emissions.

As the operating requirements shift to even more hours, i.e. high intermediate to base-load, the 590 MW SCC6-5000F 2x1 Flex-Plant™ 30 becomes the product of choice with its fast-start capability without compromising traditional high F-class combined cycle efficiency. This product provides significantly reduced start-up times with minimized start-up emissions.

Diligent use of proven technologies in the plant integration means that the operating flexibility benefits offered by these products will be provided without adverse impact on reliability or availability. And further improvements being made to them will offer even greater benefits in the future. As such, Siemens' SGT6-5000F gas-turbine-based Flex-Plant™ product portfolio offers the US electric utility industry three high-value solutions to meet virtually any of its present and future needs to provide reliable, environmentally compatible and efficient power generation.

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