Fast cycling and rapid start-up: new generation of plants achieves impressive results

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Author:
Lothar Balling, Siemens AG,
Erlangen, Germany

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Fast cycling and rapid start-up: new generation of plants achieves impressive results

In last month's issue an analysis of the operational characteristics of various power generation technologies (pp 61-65) concluded that modern combined cycle power plants, with cycling and fast start capabilities, have a number of advantages in a grid where a large percentage of renewables is envisaged, as in Germany, for example. In this second article the theme of combined cycle plant operational flexibility is explored further. Recent innovations in combined cycle technology are described, as well as newly commissioned power plants that demonstrate what can be achieved.

Lothar Balling, *Siemens, Erlangen, Germany*

Figure 1. Recent combined cycle projects with enhanced flexibility and fast start capabilities

Pont sur Sambre, France

Sloe Centrale, Netherlands

Marchwood, England

Pego, Portugal

Enecogen, Netherlands

Hemweg and Diemen, Netherlands

The increased use of combined cycle plants for power generation over the past decade can be attributed to their high efficiencies, short execution times and relatively low investment costs. But now their potential for cycling and fast start-up is becoming an increasingly important selling point.

This need for increased flexibility first emerged at the end of the 1990s in the United States and the United Kingdom. The price of fuel continued to rise due to the large number of plants being built during the boom. Plants initially planned to have a base-load role were shifted to the load regime of an intermediate-load plant.

The challenge presented to projects by this changed requirement gave birth to the idea of trying to improve plant flexibility without compromising plant service life or plant efficiency.

As the market continued to develop, a demand for quicker start-ups soon followed the demand for more frequent start-ups. This market demand finally resulted in the launch by Siemens of a development project called FACY (FAst CYcling), which combined all the initial engineering ideas into a single integrated plant concept. The aim of the resulting R&D programme was to design a plant for an increased number of starts and to reduce start-up times. If possible, no limits were to be placed on the gas turbine by other power plant components, such as the heat recovery steam generator or steam turbine, during hot and warm starts.

In the course of the project, potential areas came to light where further optimisation could be achieved, although these had to wait for a second development generation to be implemented.

The major improvement offered by this second generation involved the start-up procedure. Hold points at which a plant waits until certain steam parameters have been reached were eliminated as part of the shortened "Start on the Fly" start-up procedure. In this procedure, the steam turbine is started up in parallel to the gas turbine using the first steam which becomes available after a hot start.

While the first generation FACY reduced start-up times for a hot start from 100 to 55 minutes, the second generation succeeded in pushing start-up times down below the 40 minute mark.

The first plants incorporating the features of both the first and second generations of the

Figure 2. The rise of renewables (EU-27)

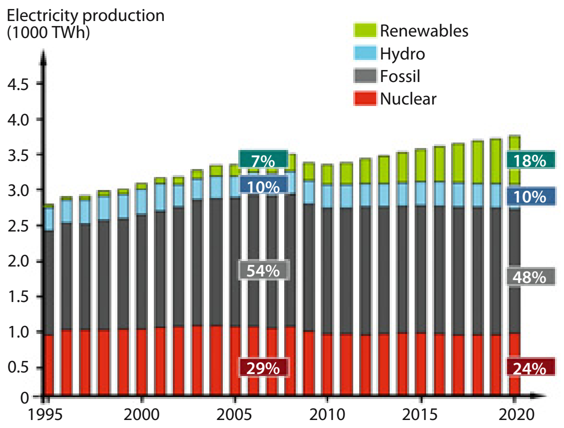
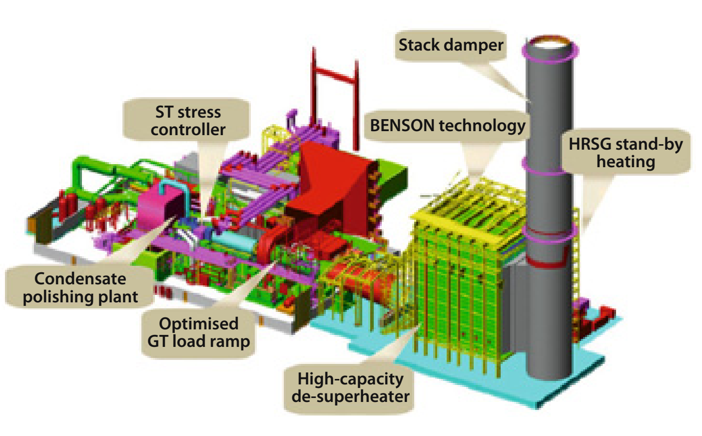


Figure 3. Main features of the Fast Cycling (FACY) concept



FACY concept have now entered commercial operation (Figure 1).

A good example is Sloe Centrale, a 2 x 430 MW F-class single shaft plant in the Netherlands, where 30-minute start-up times were recorded during acceptance tests, while achieving over 59% net efficiency. Equally good results have been exhibited by other newly commissioned plants. This means that the second generation of FACY has far surpassed expectations in a number of cases.

Shortening start-up times and improving starting reliability while increasing the number of starts was only one of many new requirements with respect to plant flexibility.

An increasingly important driver (as discussed in last month's article) is the growing percentage of renewables envisaged on the grid (see Figure 2). Wind and solar energy are not continuously available and difficult to predict precisely. Reserve power generating capabilities must therefore be provided which can be activated quickly. Gas turbine based plants are an obvious choice here as they can be started up at relatively short notice. The inherent inertia of other types of power generating facilities is usually much greater, making them largely unsuitable for use as a rapidly available reserve source of power. There are, of course, other fast-responding sources of power such as pumped storage. But they do not provide enough capacity to cover the renewable generating capacity in the European grid system, with the prospect of 30% renewables by 2030.

High availability and reliability power plants, such as combined cycle units, are required in order to compensate for fluctuating renewables. The requirements with respect to grid support, which are usually defined in a country-specific grid code, have recently become more rigorous for this reason.

Some of the most stringent requirements are to be found in the UK grid code. Requirements in the areas of load stabilisation at low frequencies, primary and secondary frequency response, and island operation capability have presented a particular challenge to UK operators for quite some time. However, the recently handed over 840 MW multi-shaft F-class Marchwood plant has finally demonstrated that the problem can be solved without compromising efficiency (over 58%) by introducing additional technical features and optimising the plant concept.

A decisive factor in the success of Marchwood was the integrated approach, which combined the potentials of several systems and components in a single solution, including use of gas turbine compressor optimisation, firing reserves, fast wet compression and other measures, combined with an optimised I&C/closed-loop control concept.

The new demand for extremely fast power generating availability is also becoming apparent in CCGT developers' economic assessments. Only a few years ago there were projects in which start-up times did not figure at all in the assessment, whereas now we are seeing over 100 000 €/min for some projects.

FAst CYcling concept (FACY)

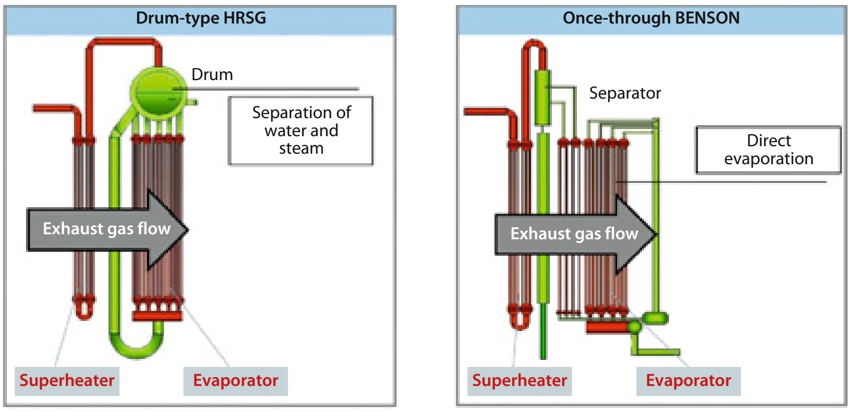
The idea of focusing plant design on an increased number of fast starts originated from market conditions and from specific projects. A multidisciplinary team of component and plant experts (for the steam turbine, gas turbine, balance of plant and auxiliary systems, I&C and steam generator) was formed by Siemens around 2002 to identify improvement potential in the existing plant concepts.

The team identified the following priorities:

- Maintaining pressure and temperature in the main components during shutdowns, by using stack dampers, auxiliary steam, etc.
- "Ready-for-operation" water/steam cycle using a fully automated start-up concept without manual operation or intervention during hot start.
- Optimised component design (eg, high capacity and fast acting de-superheaters) and plant operation to reduce material fatigue caused by load cycling.
- Flexible operation concept to allow the operator to predetermine component fatigue and to choose start-up time and ramp rate.
- Optimisation of the automation and control concept.
- New start-up sequence, "Start on the Fly", to allow a nearly unrestrained ramp-up.

Figure 3 summarises the main features of the FACY concept. These measures help reduce start-up time significantly. They are modular and are offered, configured and implemented on a project-specific basis.

Figure 4. Drum-type HRSG vs Benson-type HRSG



Preserving warm start conditions

Major heat loss from the HRSG occurs through the stack and therefore a stack damper is deployed to limit heat loss during shut-down. Cooling down of the HRSG is considerably reduced and delayed.

Furthermore, auxiliary steam can be used to heat the HRSG. These measures increase the shut-down periods for which the criteria for hot and warm starts remain applicable.

Ready-for-operation mode of water/steam cycle

Auxiliary steam is also used to maintain the water/steam cycle in a ready-for-operation mode. This means auxiliary steam is fed into the gland steam system of the steam turbine. Keeping the gland steam system in operation prevents air from being drawn into the steam turbine and the condenser. Since the steam

Figure 5. "Start on the Fly" – an improved start-up sequence

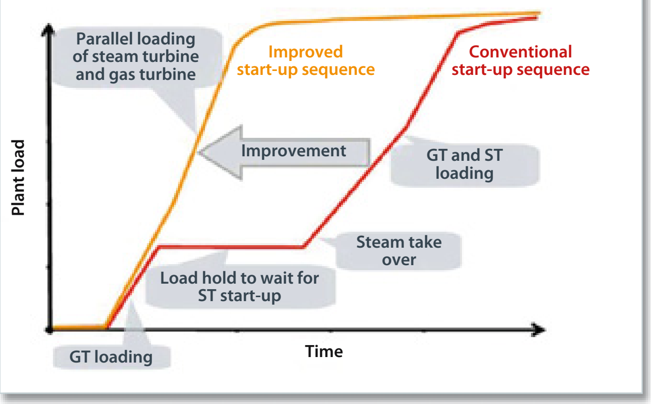
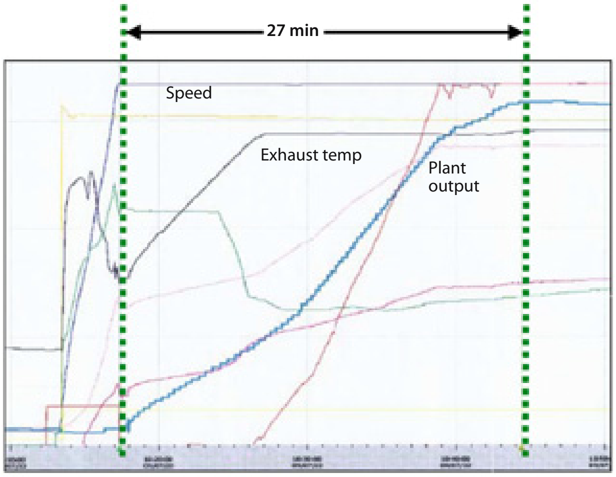


Figure 6. The 430 MW Pont sur Sambre combined cycle plant (SCC5-4000F 1S)



turbine and the condenser are sealed off from the ambient air, the condenser vacuum pumps can maintain the vacuum.

To enhance the start-up procedure, the condensate polishing plant can be used to bring the water/steam cycle within specified chemistry limits faster.

Optimised component design and plant operation to reduce material fatigue

In a conventional HRSG the high pressure drum is one of the most critical components in the start-up and ramping procedure. As a thick-walled component it is exposed to large temperature gradients and high operating pressures. Thermal stress in the high-pressure drum walls limits the load-, start up- and shut down- gradients of the HRSG.

However there is no high pressure drum in a Benson-type boiler, so these limits do not apply. The Benson boiler technology employs once-through steam generation, which means that conventional separation of steam and boiling water inside a drum is not necessary. Instead, steam is generated directly within the evaporator tubes, as shown in Figure 4.

Use of Benson technology allows the number of permissible starts and cycling events during the plant lifetime to be significantly increased, by reducing stress induced fatigue in the high pressure section of the HRSG.

Also, a temperature-controlled start-up process, using an optimised high-capacity de-superheater to limit steam temperatures during the start-up, has been developed for warm and cold starts. This reduces thermal stress in critical components of the steam turbine.

Optimising the automation

There are essentially two ways in which automation system is optimised to support improved start-up:

- Design limits are fully exploited through the use of closed-loop control instead of earlier empirically based approaches. A turbine stress controller is used to determine thermal stress based on temperature differences measured within the steam turbine and ensures that stress limits are not exceeded. The turbine stress controller makes it possible to shorten the start-up time without reducing the lifetime of heat-critical turbine components.
- Two additional start-up modes – "FAST" and "COST-EFFECTIVE" – in addition to the "NORMAL" mode have been introduced. The operator has the option of choosing the appropriate start-up mode depending on such factors as current electricity market prices. Maintenance intervals can be extended using the "COST EFFECTIVE" setting, while the "FAST" mode permits controlled fast start-up, but entails increased maintenance requirements.

The start-up procedure is automated to a level that enables hot starts with only a few operator actions, the aim being to minimise inefficient and unproductive periods during start-up preparations. Draining and venting are largely automated, for example.

Second-generation FACY – "Start on the Fly"

In addition to the features included in the original FACY concept, a procedure for parallel start-up of gas and steam turbines has been developed. It is based on monitoring and

Figure 7. The 860 MW Irsching 5 combined cycle plant (SCC5-4000F 2+1)

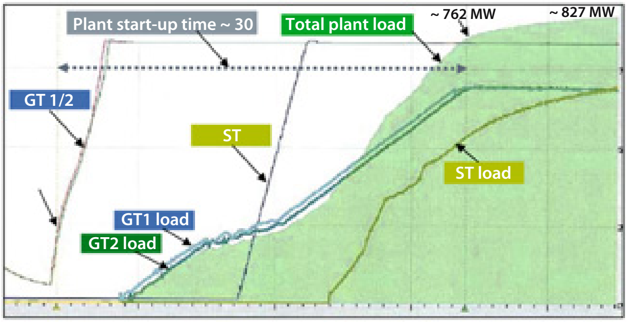
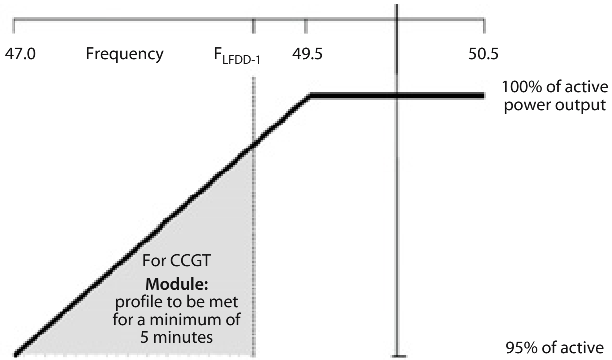


Figure 8. Load stabilisation at low frequency in accordance with the UK grid code



Note: Frequency F_{LFDD-1} is the relay trip setting of the first stage of the Automatic Low Frequency Demand Disconnection Scheme

Figure 9. The 840 MW Marchwood combined cycle plant (SCC5-4000F MS)

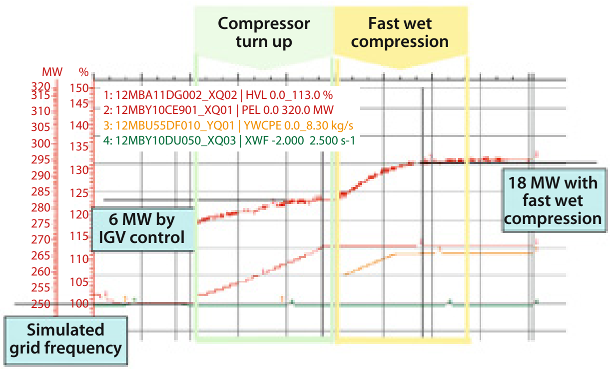


Figure 10. Load stabilisation at low frequency, Marchwood test results

controlling the temperature gradients within limits acceptable for all critical plant components and on long term turbine operating experience over a range of steam conditions. The new concept enables the plant to be started-up without any gas turbine load hold points, enabling a new start-up sequence to be implemented – see Figure 5. The main innovation is the early steam turbine starting point with earlier acceleration and loading of the turbine.

Recent operating results

The features described above have been implemented in plants across Europe and excellent results have been achieved in single shaft as well as in multi shaft configurations. Two notable examples are the Pont sur Sambre F-class single shaft plant in France and the F-class multi shaft configuration at Irsching 5 in Germany, Figures 6 and 7, respectively.

Both units have demonstrated the capability to start-up and reach full load in about 30 minutes folowing an overnight shut down, without compromising efficiency, achieving levels of over 58% and over 59%, respectively.

It is noteworthy, that the single shaft operating concept allows parallel start up of several units at a site, resulting in multiples of, eg, 430 MW, being available in around 30 minutes, as has been demonstrated at Sloe Centrale, with its two units.

Grid support

In liberalised electricity markets, the minimum requirements for power plant dynamics are set out in grid codes. Some of the most stringent requirements imposed on plant dynamics are to be found in the grid code of the UK, reflecting its island geography. Three of the most critical considerations are: load stabilisation at low frequencies; primary and secondary frequency response; and island operation capability.

Load stabilisation at low frequencies

Normal fluctuations in the balance between generation and consumption are reflected in fluctuations in grid frequency which can be compensated for by means of routine frequency control measures. The frequency can, however, also decrease or even increase significantly in the event of unusually large disturbances.

Unfortunately a decrease in grid frequency also means a reduction in turbine speed and subsequently a decrease of power output. This decrease in speed causes the compressor in a gas turbine to produce a reduced volumetric flow, thus decreasing gas turbine output if appropriate compensatory measures are not implemented.

The United Kingdom grid code stipulates that power output must be maintained for a minimum of 5 minutes in the event of a frequency drop, down to 49.5 Hz – so as to avoid further taxing of the grid due to under-frequency. If a greater decrease in frequency occurs, the grid code permits a maximum decrease in output of 5%, down to 47 Hz, as illustrated in Figure 8.

To counteract this decrease in power output, several measures for increased output can be implemented at short notice. The decrease in output can be compensated for by rapidly opening the guide vanes on the compressor. The fuel flow is increased at the same time. This can compensate for a drop in power of around 6 MW.

In unfavourable operating conditions, however, this increase in output will not be sufficient on its own. In this case Fast Wet Compression (a patented Siemens concept) can be used to mobilise a further power reserve of around 12 MW.

Fast Wet Compression consists of spraying demineralised water into the compressor inlet. The mass of the injected water increases the mass flow through the compressor. The evaporating water also cools the air flow at the compressor inlet. The air density and consequently the mass flow through the compressor increase due to this cooling process. Rapid activation of the system constitutes a challenge to control systems, as the fast increase in power output requires perfect co-ordination between the gas turbine control system and the water injection.

These grid support features have been validated and demonstrated in the Marchwood F-class multi shaft plant in the UK, at a power output of about 840 MW and over 58% efficiency (Figure 9).

Plots from the Marchwood tests are shown in Figure 10. It can be seen that an 18 MW increase was achieved (for each gas turbine) by opening the compressor IGVs and then initiating fast wet compression, thus meeting the requirement of the United Kingdom grid code.

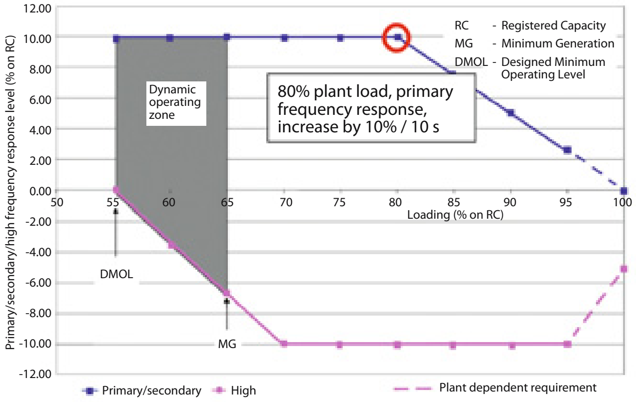


Figure 11. Frequency response at low and high frequencies in accordance with UK grid code

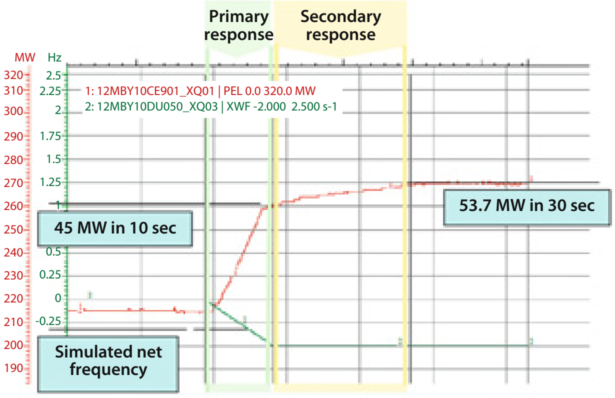


Figure 12. Frequency response test at low frequency, Marchwood, July 2009 (data for one GT)

Figure 13. Island operation test at Marchwood (data for one GT)

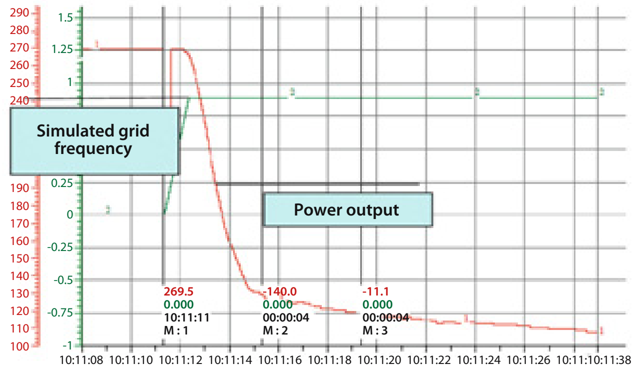
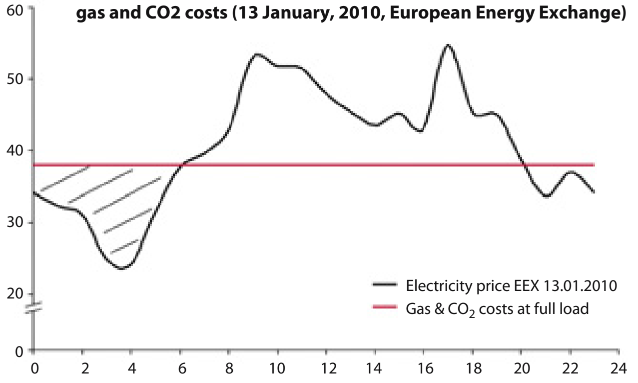


Figure 15. Typical electricity price curve (€/MWh) compared with gas and CO2 costs (13 January, 2010, European Energy Exchange)



Primary and secondary frequency response

The purpose of load stabilisation at low frequencies is to prevent further destabilisation of the grid when the frequency decreases due to major disturbances. Primary and secondary frequency responses are now required for grid support during normal operation. For this purpose the UK grid code stipulates that a power plant operating at part load must be capable of making additional power available. Figure 11 illustrates the relevant part of the UK grid code. We can see that a power plant operating at under 80% load must be able to make available at least 10% of its rated power within 10 seconds in the event of a decrease in frequency. For secondary frequency response 10% of its rated power must be made available within 30 seconds. Figure 11 shows that the requirements are reduced when the plant is operating at loads over 80%.

Unlike load stabilisation at low frequency, there is no need to look for a further power reserve in this case. The challenge lies more in the speed at which the power must be made available.

To meet the requirements of the grid code, we rely on fast repositioning of the compressor IGVs coupled with fuel control optimised to such an extent that load ramps are possible without destabilising combustion.

Figure 12 illustrates the results of tests done on the Marchwood plant and clearly shows that the required additional power is achieved both after 10 seconds and after 30 seconds. In fact, performance is significantly better than that required by the grid code in both instances.

Another aspect of the grid code, also shown in Figure 11, is high frequency response, namely that load must be reduced by 10% of rated power within 10 seconds in the event of over-frequencies of up to 500 mHz. However, when it comes to load reduction the island operation requirement (see next section) is even more stringent.

Island operation capability

The primary objective of island operation capability is to stabilise the grid, in the event of excess power and an abrupt drop in consumption within an islanded portion of the grid, resulting in a very rapid frequency increase. The power plant must react to this frequency increase by throttling back to stabilise the frequency, thus avoiding a forced shut-down due to over-frequency.

Uncontrolled shut-down of power plants can result in a grid collapse, which is why the UK grid code stipulates that power plants must be capable of rapidly decreasing from rated power to the design minimum operating level (DMOL). The DMOL must not be smaller than 55% of rated power in this case. This load reduction must be effected sufficiently quickly that the island frequency remains below 52 Hz. Grid studies based on the UK National Grid requirements show that the load reduction must take place within around 8 seconds.

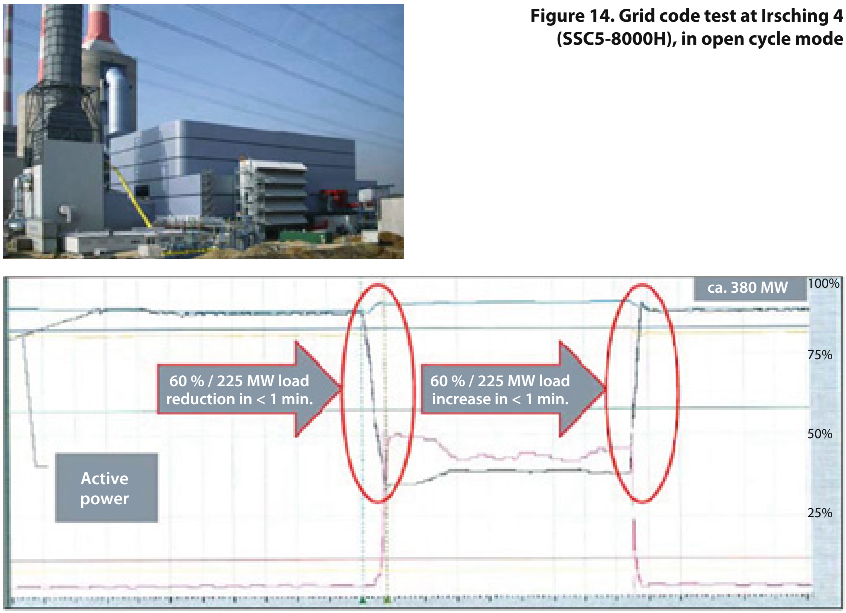


Figure 14. Grid code test at Irsching 4 (SSC5-8000H), in open cycle mode

The power plant must detect island formation automatically and take immediate action. As soon as island operating mode is activated, permitted load change ramps are set to the maximum value. The inlet guide vanes in the gas turbine compressor are closed without delay. At the same time the various closed-loop controls ensure that the power is decreased at the maximum rate of change for load. Maintaining flame stability and avoiding potential flash backs in the combustion system are the main objectives of closed-loop control optimisation, so as to avoid emergency shutdown of the gas turbine.

Figure 13 illustrates an island operation test at Marchwood. The gas turbine output was decreased by 52% within 4 seconds as the result of a simulated fast frequency increase of 0.9 Hz, without initiating a plant trip. A further decrease of 4% was achieved in the following 4 seconds. Thus performance again exceeded grid code requirements.

Transfer to the H

Meanwhile, these basic plant features demonstrated in F-class plants are being transferred also to H-class technology and have already been validated in open cycle operation at Irsching 4 (Figure 14), demonstrating that even this latest and highest efficiency technology is capable of supporting the same stringent grid code requirements.

The bottom line: benefits to the operator

The previous sections clearly demonstrate that FACY and Start on the Fly permit a reduction in start-up times as well as an increased number of start-ups, enabling nightly power plant shut-downs. The latter offers two additional benefits:

- Carbon dioxide emissions are minimised by shortening inefficient plant start-ups. Maximum electrical efficiency is reached faster and total emissions are reduced.
- Since nightly shutdowns and reliable start-ups become economically feasible, overall carbon dioxide emissions are further reduced as inefficient overnight parking at

load is avoided. Other power plants within the grid can then be operated at full load and maximum efficiency.

Operators benefit from this, primarily through fuel savings and a reduction in carbon dioxide emissions during the start-up phase. Shortening the start-up time by using Start on the Fly for a hot start offers an estimated added value of more than 3 million euros alone, assuming that the savings described above are realised over the service life of a 430 MW power plant.

The option of disconnecting the plant from the grid overnight offers enormous potential in the form of savings in operating costs.

Night-time electricity prices have been at such a low level in the European system that a combined cycle power plant could no longer be operated at a profit during the night due to high gas and carbon dioxide costs (see Figure 15). To minimise these losses, power plants are operated at part load or are shut down altogether at night.

Reducing the load already brings about a significant reduction in losses. However when the load decreases, so does overall efficiency, meaning that gas and carbon dioxide costs can only be reduced disproportionately.

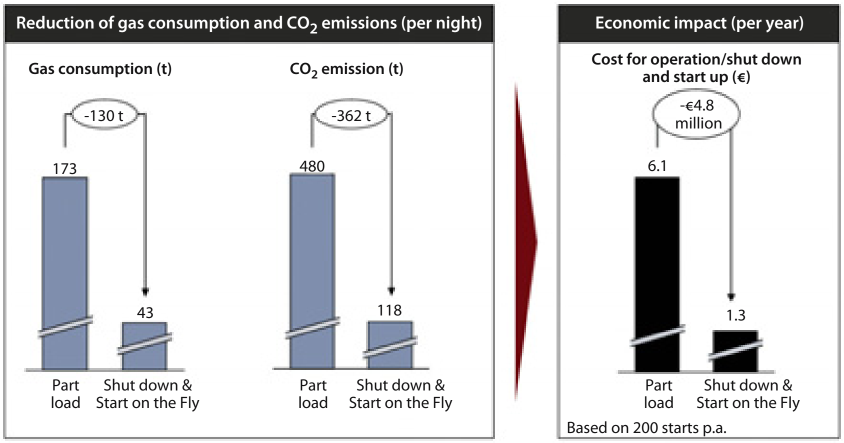
In addition to the positive effect of load reduction, shutting a power plant down at night can achieve other significant benefits. Only shut-down and start-up costs are incurred, for example. Restrictions relating to the permitted number of start-ups for the plant have been significantly reduced, thanks to the FACY programme. FACY and Start on the Fly have also significantly reduced start-up times. The result is lower gas consumption and lower carbon dioxide emissions, providing the power plant operator with an additional economic benefit for every start.

Figure 16 shows the carbon dioxide and fuel savings which can be achieved by night-time shutdown using FACY compared with night-time part-load operation at about 25%. We can see that the power plant in this example can avoid up to 130 tons of gas consumption and 362 tons of carbon dioxide emissions per night through night-time shutdown. This increases the annual power plant profit by 4.8 million euros as compared with night-time part-load operation.

Today grid support features arise primarily from the grid access requirements of the individual countries. No monetary valuation of the additional plant flexibility is included in tender specifications as yet. For this reason today's plants are designed purely based on grid code specifications. Depending on the level of electricity market liberalisation, however, the various flexibility features enable additional earnings to be generated, in particular by participating in the frequency reserve market.

Another potential benefit is that plants with high reliability and operational flexibility, able to cope well under disturbed grid conditions, can expect to be prioritised for dispatch. MPS

Figure 16. Savings in gas consumption and avoided CO_2 emissions resulting from night-time shutdown. This is based on a gas price of 20.2 €/MWh, CO_2 costs of 2.88 €/MWh and a night-time electricity price of 29.4 €/MWh. The performance data are based on an SCC5-4000F single-shaft plant with a cooling tower



Severn Power handed over

One of the latest additions to the fleet of flexible Siemens combined cycle plants in commercial operation is Severn Power, Uskmouth, near Newport in Wales, UK. This was handed over to Dong Energy on 26 November 2010, one week ahead of schedule. The 834 MWe F-class single-shaft plant is equipped with many of the cycling and fast start-up features described in the main article, and, like other plants mentioned there, is able to achieve full output in only 30-35 minutes following an overnight shut down.

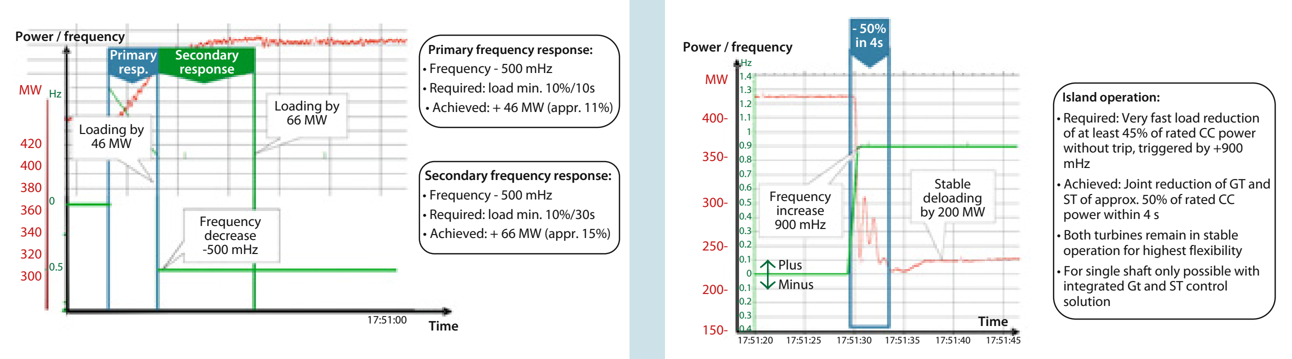
With Fast Wet Compression and other features, tests at Severn have indicated that its performance in terms of UK grid code support is at least as good as that of Marchwood (see pp 39-40).

The plant's high degree of operating flexibility also means that it is capable of very quickly compensating for the fluctuating feed-in from wind turbines.

Use of an air-cooled condenser instead of a cooling tower and application of an innovative waste water concept also minimises water consumption.

Efficiency is about 58% and, thanks to advanced burner technology, the plant's nitrogen oxide emission levels are very low, around 15 ppm.

In terms of health & safety during construction, the project has also been exemplary, clocking up more than three million working hours without a lost time accident, with over 1200 workers on the site at peak times.



Results of grid code support tests at the new Severn Power combined cycle plant

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Siemens Energy, Inc.
4400 Alafaya Trail
Orlando, FL 32826-2399, USA

For more information, please contact
our Customer Support Center.
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