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STATE OF THE ART STEAM TURBINE AUTOMATION FOR OPTIMUM TRANSIENT OPERATION PERFORMANCE

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ABSTRACT

The growing share of renewable energies in the power industry coupled with increased deregulation has led to the need for additional operating flexibility of steam turbine units in both Combined Cycle and Steam Power Plants.

Siemens steam turbine engineering and controls presently have several solutions to address various operating requirements:

- Use of an automatic step program to perform startups allows operating comfort and repeatability.
- 3 start-up modes give the operator the flexibility to start quickly to meet demand or slowly to conserve turbine life.
- Several options for lifetime management are available. These options range from a basic counter of equivalent operating hours to a detailed fatigue calculation.
- Restarting capabilities have been improved to allow a faster response following a trip or shutdown.
- In addition to control of speed, load and pressure, special control functions provide alternative work split modes during transient conditions.
- Optimum steam temperatures are calculated by the steam turbine control system to achieve optimum start-up performance.
- Siemens steam turbines are also capable of load rejection to house load, some even to operation at full speed, no load.

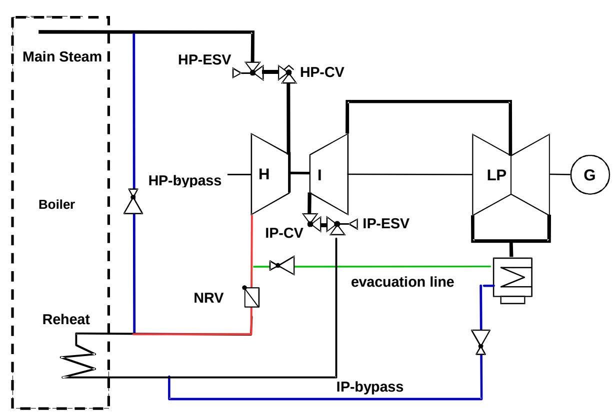
Several plants are already equipped with these solutions and have provided data showing they are operating with shorter start-up times and improved load rejection capabilities.

Finally Siemens of course continues to pursue future development.

INTRODUCTION

Siemens steam turbines (ST) for application in large power plants within a power output range from 100 MW to 1000 MW typically consist of high pressure (HP), intermediate pressure (IP) and low pressure (LP) sections. These can be placed either in separate or combined casings. A typical arrangement in a steam power plant (SPP) includes both HP and IP bypass stations and an HP evacuation line. The latter is required due to discharge of the HP section after an ST trip to reduce the pressure inside the HP turbine. HP steam from the steam generator first passes through HP emergency stop valves (ESV) and HP control valves (CV) before entering the HP turbine. During start-up and shut-down as well as load rejection or trip, HP steam is bypassed to the cold reheat line. HP exhaust steam passes the non return valve (NRV) and enters the steam generator to be reheated. The reheated steam passes IP ESV and IP CV or may be routed via the IP bypass to the condenser. After flowing through the IP section the steam is routed to the LP section and expands to the condenser pressure (graphic 1).

Graphic 1
SPP system diagram



Basically automation is designed to provide safe and reliable operation within specific design-based limits. For steam turbines with high rated temperature and pressure, both protection against instant failures and a lifetime of more than 30 years has to be ensured. As a consequence several limitations exist, most of them concerning temperature and pressure, both for steady state and transient operation.

Automation provides various opportunities to use operational limits to the maximum and achieve the highest possible flexibility. Above all, the control system nowadays enables complex calculations and simulations. Using this capability, existing set points can be reviewed with regard to conservatism and may be adapted for “part load” situations. This especially applies to permissible operating time.

AUTOMATIC START-UP AND SHUT DOWN

Siemens steam turbines are equipped with an automatic start-up and shut down sequence as a standard since the early 80s.

The steam turbine can be started up safely and within an optimum time with the aid of an automatic start-up system. This meets economic requirements which prescribe the shortest possible start-up time and high plant availability.

The task of the turbine master control program is to bring the turbine into a state which allows safe and reliable transition of the steam turbine from the shutdown state to load operation.

Generally two modules are available:

1. start-up and shut down of auxiliary systems
2. start-up and shut-down of the steam turbine

Both are step sequences with each step sending commands to controllers and actuators and waiting for feedback signals to move on to the next step.

Start-up and shut down of auxiliary systems: This automatically starts up the following systems:

– Lube oil supply
– Seal steam system and evacuation pumps
– Control fluid supply for turbine valves and bypass valves

Any other auxiliary system can be added specifically.

The program brings the steam turbine and the bypass system up to turning gear operation of the steam turbine and bypass operation.

Start-up and shut-down of the steam turbine: After the auxiliary systems have been started up and brought into a steady state, which can either be achieved using "Automatic start-up control for auxiliary systems" or by starting the auxiliary systems manually, the "Automatic start-up control for turbine-generator" transfers the steam turbine from turning gear operation to power operation.

The start-up program is complete as soon as the turbine controller has been changed over to inlet pressure control (CCPP) or load control (SPP).

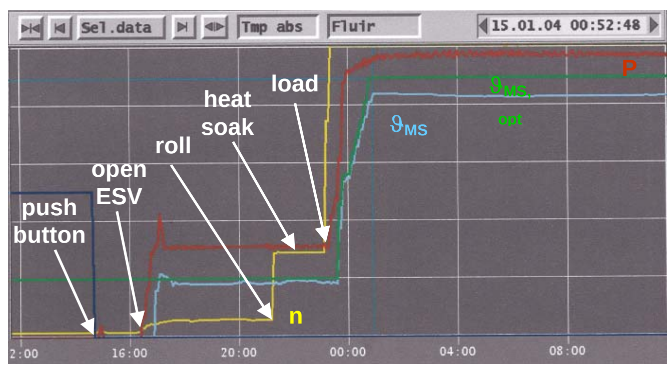
The automatic shutdown program brings the turbine-generator from load operation to a defined state in which the turbine valves are completely closed and the generator separated from the grid (for CCPP single shaft the clutch disengaged). Furthermore, it takes all actions required to allow the turbine to coast down to turning gear operation.

The program interfaces the following systems:

– lube oil system incl. oil pump tester
– turbine drain system
– automatic turbine valve test
– turbine controller
– turbine stress evaluator

Operational data shows that the automatic start-up program provides quick start-up times (graphic 2). At the same time all operational limits are used to the maximum allowed but not violated. After checking that all auxiliary systems work properly and steam lines upstream of the turbine are drained, the emergency stop valves (ESV) are opened. This allows steam to pass through warm-up lines and pre-warm the control valves (CV). Once steam purity is achieved the program sets a speed set point and opens the CV. The steam turbine is heat soaked at warm-up speed as required. This mainly applies for cold starts. As soon as temperature requirements are met and the operator has decided to run up since vibrations and eccentricities are within allowable limits, the program sets the speed set point to synchronization. After further temperature criteria are met the program makes the unit synchronize automatically and go to the load set point as entered by the operator. After the bypass station is closed the start-up program is finished.

Graphic 2
OM graph of automatic cold start



TURBINE STRESS CONTROLLER (TSC)

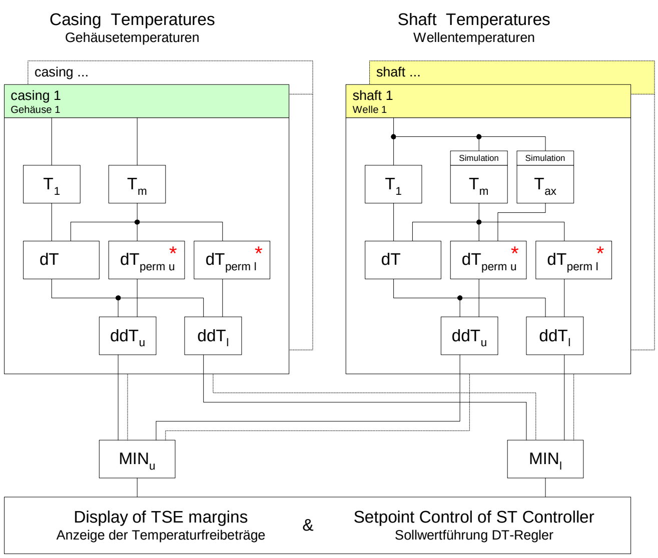
The Turbine Stress Controller (TSC) basically performs two tasks:

– calculating and monitoring the operational heat stresses of the turbine during every operational phase (Turbine Stress Evaluation functions - TSE) for three different start-up modes,

– calculating continuously and overall the component fatigue from these data (Life Time Expenditure functions – LTE).

The TSC determines the thermal stresses of all representative turbine components and uses the actual temperature differences (dT), which represent the thermal stresses, in comparison with the permissible values (dT_{perm}) to calculate the temperature margins (ddT). This achieves a continuous optimization between material stresses on the turbine and the largest possible flexibility in order to react to operational changes (graphic 3).

Graphic 3
Turbine stress evaluator function

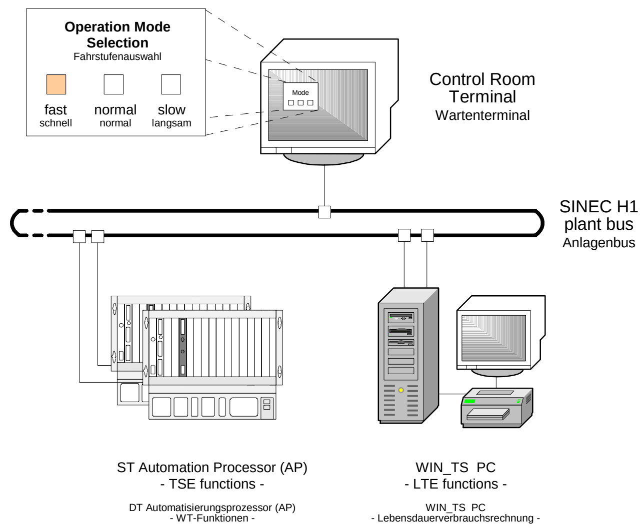


The number of channels is not limited and can be applied to different manufacturers' designs.

In parallel the thermal situation of the relevant turbine parts is permanently monitored for the calculation of lifetime consumption. This PC based application runs on the WIN_TS PC platform, which was developed for several turbine diagnostic functions. The PC is connected to the plant bus for signal transfer of necessary temperature and other process data. A PC modem for remote system support can also be provided.

Three different operation modes can be selected (slow, normal, fast) to adjust steam turbine operation mode to the grid situation (graphic 4). The start-up modes can be pre-selected by the operator, following grid requirements. Thermal stress and as a result life consumption of the ST is accumulated and monitored. The fast start-up mode (e.g. 800 ST starts) reduces ST warm and cold starting time remarkably, but causes increased ST life consumption per start. In contrast the slow start-up mode (e.g. 8000 ST starts) reduces thermal stress and, thus, saves life consumption. But the slow start-up mode results in longer ST starting times. The start-up mode 'normal' means the Siemens standardized cycling duty (2200 ST starts). Temperature margins will be calculated for each mode in parallel. All measured temperatures and active calculated temperature margins are indicated and recorded.

Graphic 4
Turbine stress controller arrangement



In parallel the thermal situation of the relevant turbine parts is permanently monitored for the calculation of lifetime expenditure.

COUNTER FOR EQUIVALENT OPERATING HOURS

As an alternative to the complex fatigue calculation described above a simple counter for equivalent operating hours (EOH) is provided.

Both the actual operating hours of the turbine generator and the number of starts are taken into consideration and are combined to help select the inspection date.

Details of equivalent operating hours, actual operating hours and actual starts are displayed on the OM.

The equivalent operating hours are calculated as the sum of actual operating hours, $\sum EOH_{operation}$, and the sum of equivalent operating hours for startup procedures, $\sum EOH_{startup}$.

$$\sum EOH = \sum EOH_{operation} + \sum EOH_{startup}$$

The equivalent operating hours for startup procedures are calculated for each start from the quotient of a unit specific design number X and the number of permissible starts N_{perm}:

$$EOH_{startup} = X / N_{perm}$$

X equivalent hours are specified for non-steady-state processes in the component design.

N_{perm} depends on the expansions or wall temperature differentials occurring during a startup according to the curve of number of cycles to failure.

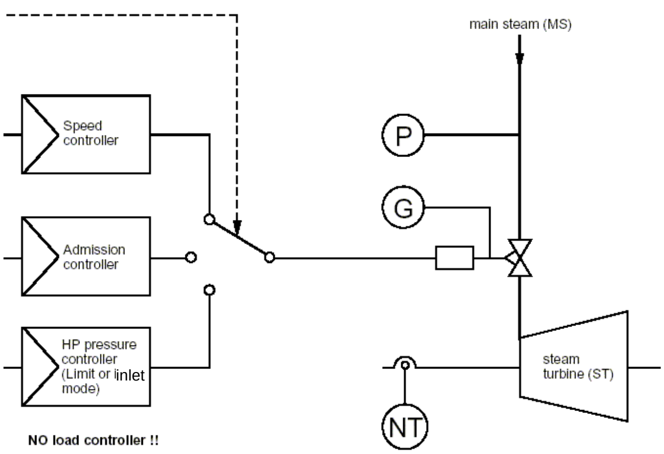
STEAM TURBINE CONTROLLER

The digital Steam Turbine Controller (STC) controls the steam flow that is passed through the control valves to the turbine. Depending on the specific requirements of each operational phase, the STC controls the following variables:

– speed
– valve admission or load
– steam pressure

In a CCPP process the steam flow for the steam turbine is supplied by the heat recovery steam generator (HRSG). Since the steam production depends on the loading state of the gas turbine(s), the gas turbine controller(s) (GTC) regulates the load of the entire unit. In this case the STC is not at all involved in the load control (graphic 5).

Graphic 5
STC (CCPP) basic scheme



Principle of Steam Turbine Controller, simplified

The STC functions are implemented in the digital automation system. The output signals of the master controllers for the speed, valve admission or load and HP/IP/LP pressure are led through selection logic to the subordinated valve position controllers and then to the load amplifiers for the actuators. The electro-hydraulic actuators (EHA) provide the hydraulic control valve positioning forces. This structure of the STC, in conjunction with an appropriate parameter selection, provides both an optimum load operation with the grid and a stable grid-island operation. The STC can be easily and flexibly adapted to the general unit control concepts, such as turbine follow mode, boiler follow mode, coordinated operation etc.

The digital STC performs the following particular tasks:

- Starting up the turbine generator with the speed controller, starting off from turning speed of the turbine. Here both the thermal stressing of the turbine is monitored (by turbine stress evaluator (TSE) functions) and the turbine generator speed is prevented from remaining in critical speed ranges.
- Matching the turbine speed with the grid frequency by means of an automatic synchronizer.
- Loading the turbine generator with the admission or load controller starting from no-load while taking the permissible loading gradients into consideration. The maximum permitted gradient is set in accordance with the load capabilities of the steam generator for both applying and removing load. However, to protect the turbine, they will be limited by the temperature margins determined by the TSE.
- Throttling of the turbine control valves by the pressure controller in case of a steam generator malfunction or excessive load demands.
- Transferring control from admission control to inlet pressure control (sliding pressure operation as a function of load).
- Limiting turbine overspeed below the overspeed trip set point in the event of load rejections.
- Ability to ride out a full load rejection: In the event of an overspeed condition caused by a load rejection due to disconnection of the generator from the grid, it reduces speed to a value below the overspeed trip setting for the turbine-generator. Once the generator has been disconnected from the grid, the controller switches to speed control.
- Grid frequency support by means of a precise linear frequency/output curve during power operation.
- Dynamically stable control of step load changes and the resulting new grid configurations. Parallel operation is possible within a power island (islanding mode) that has become separated from the grid.

In addition to the described general ST controller tasks the Siemens STC has specific features with regard to work split modes:

As standard, HP and IP valve opening is staggered. IP valves open from 0% to 100% at a controller output of 17% to 70%. During acceleration and operation at heat soak speed IP CV already open at 4% controller output (graphic 6).

HP exhaust steam temperature controller:

In the event of non-steady-state processes, steam temperature in the rear region of the HP blading must not exceed a set maximum value, in order to limit both thermal stress in the blading and differential expansion. Steam flow through the HP turbine section can be manipulated appropriately to maintain temperature in the exhaust region below permissible values.

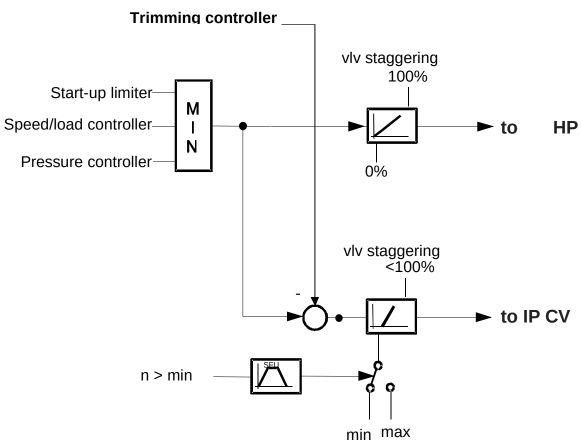
The HP steam control valve positions are coordinated appropriately with those for the IP steam control valves via the HP/IP trimming function. This ensures that temperatures within the HP turbine section do not exceed the permissible limit during any of the non-steady-state operating processes such as load rejection, startup and shutdown with any of the various main steam conditions or condenser pressure levels active.

The valve position is trimmed using a limit controller for HP exhaust steam temperature which throttles the IP steam control valves when a variable set point derived from the shaft temperature is exceeded.

HP pressure ratio controller:

In the event of low steam flow through the HP turbine section e.g. at synchronization speed, the HP exhaust temperature will increase. Below a certain pressure ratio (pressure before blading divided by pressure after blading) the flow is extremely low. As a consequence the HP exhaust steam temperature measurement is no longer representative of the actual temperature rise inside the HP blading. Under this operating condition, the HP section is monitored by the HP pressure ratio protection system. To prevent unnecessary response of the pressure ratio protection system, appropriate trimming of control valve position is first implemented with the aid of the HP pressure ratio controller.

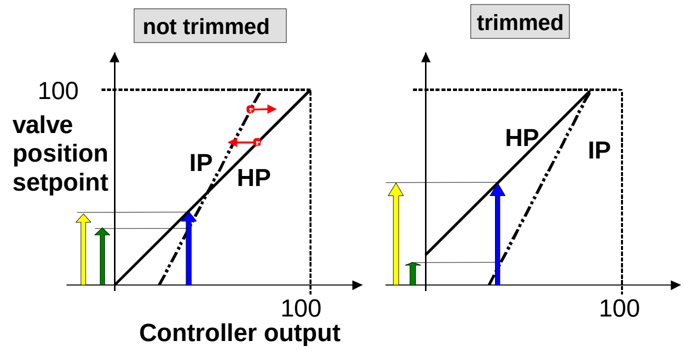
Graphic 6
Trimming controller influence



Both trimming controllers act on the staggering: Depending on the deviation of actual value and set point the opening of the HP valves is shifted forward and the opening of the IP valves is shifted backward. This means that at a similar controller output which corresponds to an associated speed or load set point, the position of HP and IP valves is different (graphic 7).

Finally the whole shift in valve position causes a shift in mass flow from IP to HP.

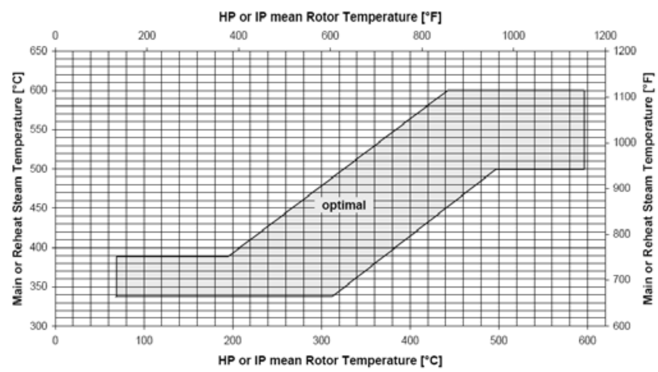
Graphic 7
Trimming effect



OPTIMUM STEAM TEMPERATURE

The monitoring and limitation of thermal stress on thick-walled turbine components constitute restrictive control of (non-steady state) steam turbine-generator operation. The steam parameters must be within allowable limits (graphic 8).

Graphic 8
Steam temperature limits for roll-off



It is not effective for the operator to follow these wide ranges.

Therefore the basic idea which led to the development of a function for calculating optimum main steam and hot reheat temperatures was to calculate optimum steam temperatures which permit optimized startups of the steam turbine within the framework of restrictive limits. In this case an optimum startup is one which avoids delays due to unfavorable though permissible steam temperature settings.

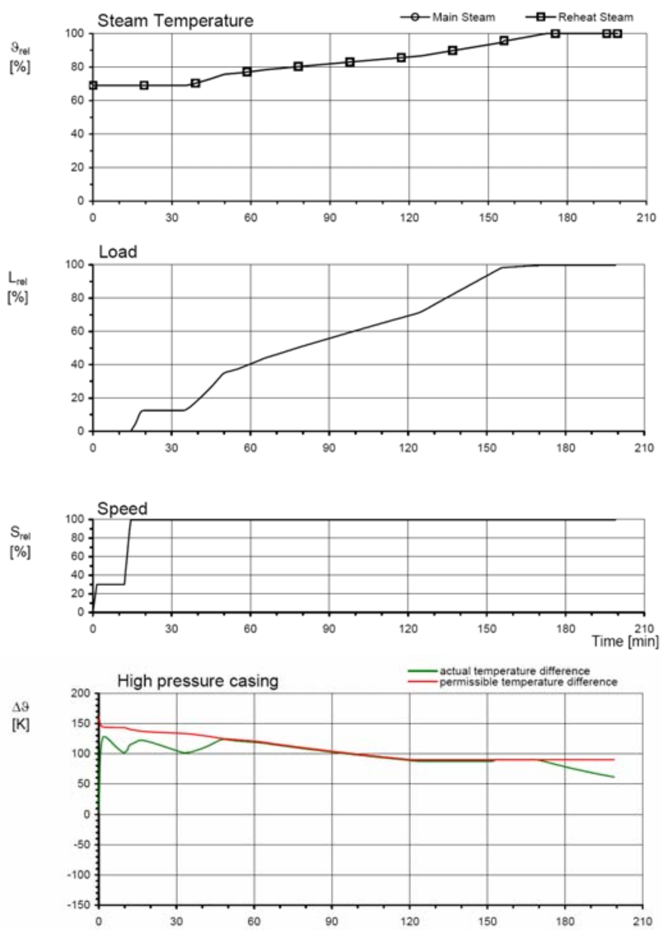
Main steam and hot reheat temperatures which permit an optimum startup process should be calculated for the various operating phases during startup based on the permitted thermal stress of the monitored components and to avoid any differential expansion holds.

Calculation of the optimum main steam and hot reheat temperatures of the steam turbine is intended for further use on the unit control level, in order to design a steam temperature control which is optimum for the unit.

Because the steam temperature is set on the steam generator, a temperature loss between the steam generator and the turbine is worked into the calculation.

Calculated start-up curves show that permissible stress limits are used to the full extent if the steam temperature is defined over time (graphic 9).

Graphic 9
Calculated cold start-up curve



LOAD REJECTION CAPABILITY

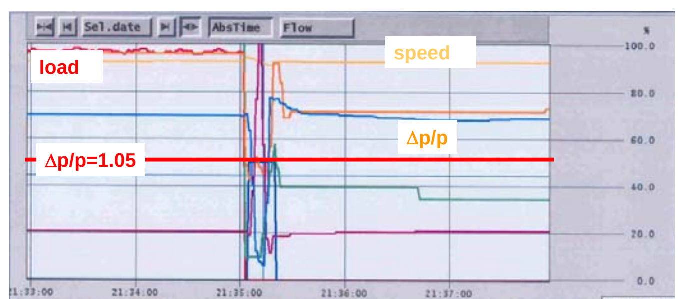
Large-size power fluctuations on the grid must not result in instability of the speed/load controller nor in damage to the steam turbine. This type of power fluctuation is rapidly detected by the steam turbine controller. To trigger appropriate action, signals are sent to the speed/load controller.

In the event of opening of the generator breaker the ST is to operate at full speed no load.

The main challenge for this load case is windage in the HP turbine resulting from operation at low flow and high backpressure. Windage means, that the energy flow is reversed. The mechanical energy from the turbine shaft is converted to thermal energy, which increases the temperature of the steam and the turbine components. To avoid any mechanical damage the ST is automatically protected against both high exhaust temperatures and low pressure ratio of inlet to exhaust representing the steam flow. The trimming controllers described above ensure that as much steam as possible is routed to the HP turbine. However it was required to design an intelligent logic for pressure ratio protection to allow limited time of operation at low pressure ratio. Windage power P depends on mean stage diameter D_m, blade height h, speed n and density ρ: $P \sim D_m^4 \; h \; n^3 \; \rho$. Therefore the protection limit is adapted to the actual exhaust pressure.

These variable protection limits enable successful load rejection proved by operational data of a CCPP in Korea (graphic 10). Tripping the ST when the pressure ratio Δp/p falls below 1.05 for longer than 10 sec. applies for nominal conditions. But during a load rejection the exhaust pressure naturally decreases due to closing of the control valves and opening of the evacuation line. This allows longer permissible operating time.

Graphic 10
Load rejection data



Plant ID code	Text	LL	Val.	UL	Unit	Cursor
10MYA01CS901 XQ01	SPD ACT VAL	0.000	59.989	65.000	s-1	59.575
10MKA01CE003A XQ01	ST GEN ACTIVE POWER	0.000	0.478	210.000	MW	0.478
10LBC41CG051B XG01	HP DUMP VALVE	0.000	0.000	2.000		1.000
10MAA12FG151 XQ01	HP CTRL-V1 POSN MEAS	0.000	6.897	20.000	%	3.955
10MAA50CP011 XQ21	HP DIFFERENTIAL PRESSURE	0.000	1.460	2.000		0.900
10MAA50CP011 XQ02	HP DIFFERENTIAL PRESSURE	0.000	21.121	100.000		57.436
10LBC40CP001 XQ01	PRES CLD REHT BEF NRF	0.000	27.484	40.000	bar	2.656

FUTURE DEVELOPMENTS

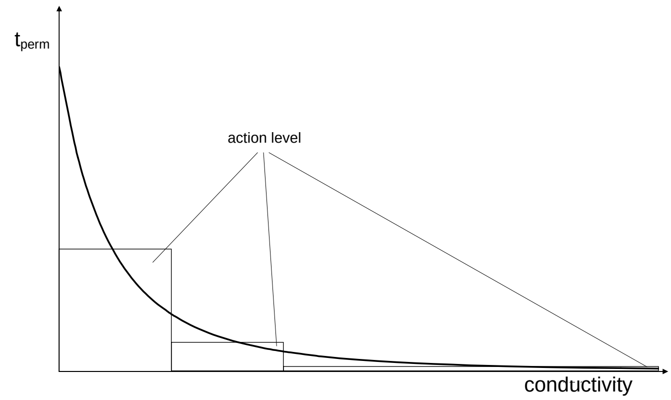
The described I&C features are subject to continuous improvement based on operational feedback, new turbine designs and customer requirements.

Currently, for example, the ***optimum steam temperature*** is being ***enhanced*** to support both “load controlled” and “temperature controlled” start-up. Load control is most recently requested by customers for cycling plants. Using external water injection the steam temperature can be controlled independent of the HRSG load. This allows for loading the gas turbine as quickly as possible without increasing the steam temperature too fast causing high thermal stress on the ST. Therefore, this start-up procedure focuses on fast start-up times in terms of generating as much electricity as quickly as possible.

As described above, the current optimum steam temperature is based on temperature controlled start-up. In this case the steam temperature is to be increased as fast as possible to run the plant most efficiently even in part load. This is how Siemens' customers used to operate their plants in the past.

In the future there will be two calculations for the customer to chose. This will then also comply with the permissible temperature range presented above (graphic 8).

Another project supporting increased operational flexibility by intelligent I&C solutions focuses on ***permissible limits for steam purity***. Generally the presence of corrosive impurities in steam can cause damage to turbine components by corrosion, stress corrosion, corrosion fatigue and erosion-corrosion. Caustic, salts, and acids (including organic acids and carbon dioxide) must be strictly controlled. Steam purity is currently defined by contents of Sodium (Na), Silica (SiO_2), Iron (Fe) and Copper (Cu) as well as electrical conductivity. Whereas the elements' content can only be monitored by sampling, conductivity is measured continuously. To account for increased impurities during start-up, increased conductivity is allowed for a limited time. Currently limit set points are classified according to so-called action levels [1]. This results in a step function. It is difficult to fully utilize the action levels, because the permissible time intervals of the different action levels differ considerably. In order to not exceed the permissible times and to avoid associated, additional fatigue the steam turbine has to be operated conservatively. This again results in limited flexibility especially concerning start-up time. In addition, manual monitoring requires considerable operator work. To improve the overall situation the relation between conductivity and permissible operation time has been expressed by a steady function (graphic 11) which can be implemented in the I&C for automatic monitoring.



Graphic 11
Permissible operating hours over conductivity

NOMENCLATURE

CCPP: Combined Cycle Power Plant
CV: Control Valve
Δp: pressure difference
$\Delta\vartheta$: Temperature Difference
D_m: mean Diameter
ddT: Temperature Margin (Temperature Difference Differential)
dT: Temperature Difference
dT_{perm}: Permissible Temperature Difference
EHA: Electro-Hydraulic Actuator
EOH: Equivalent Operating Hours
ESV: Emergency Stop Valve
GT: Gas Turbine
h: Height
HP: High Pressure
HRSG: Heat Recovery Steam Generator
I&C: Instrumentation and Controls
IP: Intermediate Pressure
L_{rel}: Load in percent
LP: Low Pressure
LTE: Life Time Expenditure
MS: Main Steam
n: speed
N_{perm}: Permissible Cycles
OM: Operating Monitor
p: Pressure
P: Power
PC: Personal Computer
ρ: Density
S_{rel}: speed in percent
ST: Steam Turbine
STC: Steam Turbine Controller
STPP: Steam Power plant
ϑ_{rel}: Temperature in percent
t_{perm}: permissible time
TSC: Turbine Stress Controller
TSE: Turbine Stress Evaluator

CONCLUSION

Operational flexibility has recently become an important issue for steam turbines.

Intelligent I&C solutions support using operational limits to the optimum. This paper shows several examples of such control features:

- Step programs are designed for shortest start-up times and optimum reliability through repeatability.
- Different start-up modes provide the option to chose between fast, medium and economic start-ups
- Fatigue monitoring ensures continuous information on residual turbine life.
- Calculated optimum steam temperatures support optimum total plant control during start-up.
- Protection and monitoring circuits are equipped with physically based permissible operating times. The associated highest flexibility even enables operation like load rejection to full speed no load.
- The steam turbine controller includes work split modes to get the optimum distribution of steam flow between HP and IP turbine.

This flexible operating performance of Siemens ST is documented by several examples of operational data.

Siemens continues to enhance ST controls to further optimize operation to the permissible limits.

PERMISSION FOR USE

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