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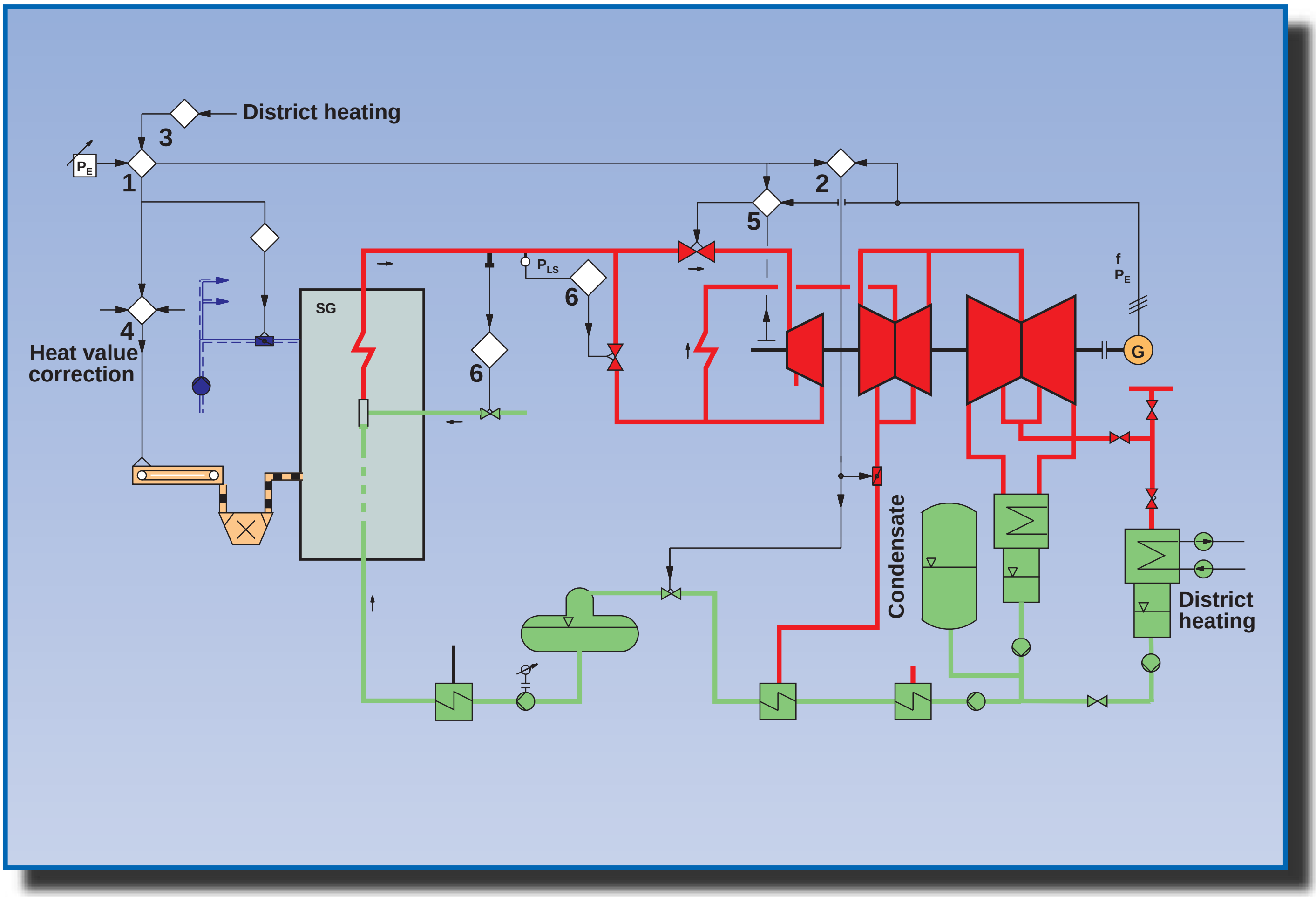
Modern Control Algorithms and Strategies for Efficient Process Control with the ME 4012 Distributed Process Control System



1 Block model (smooth load control)
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Subject to change without notice.

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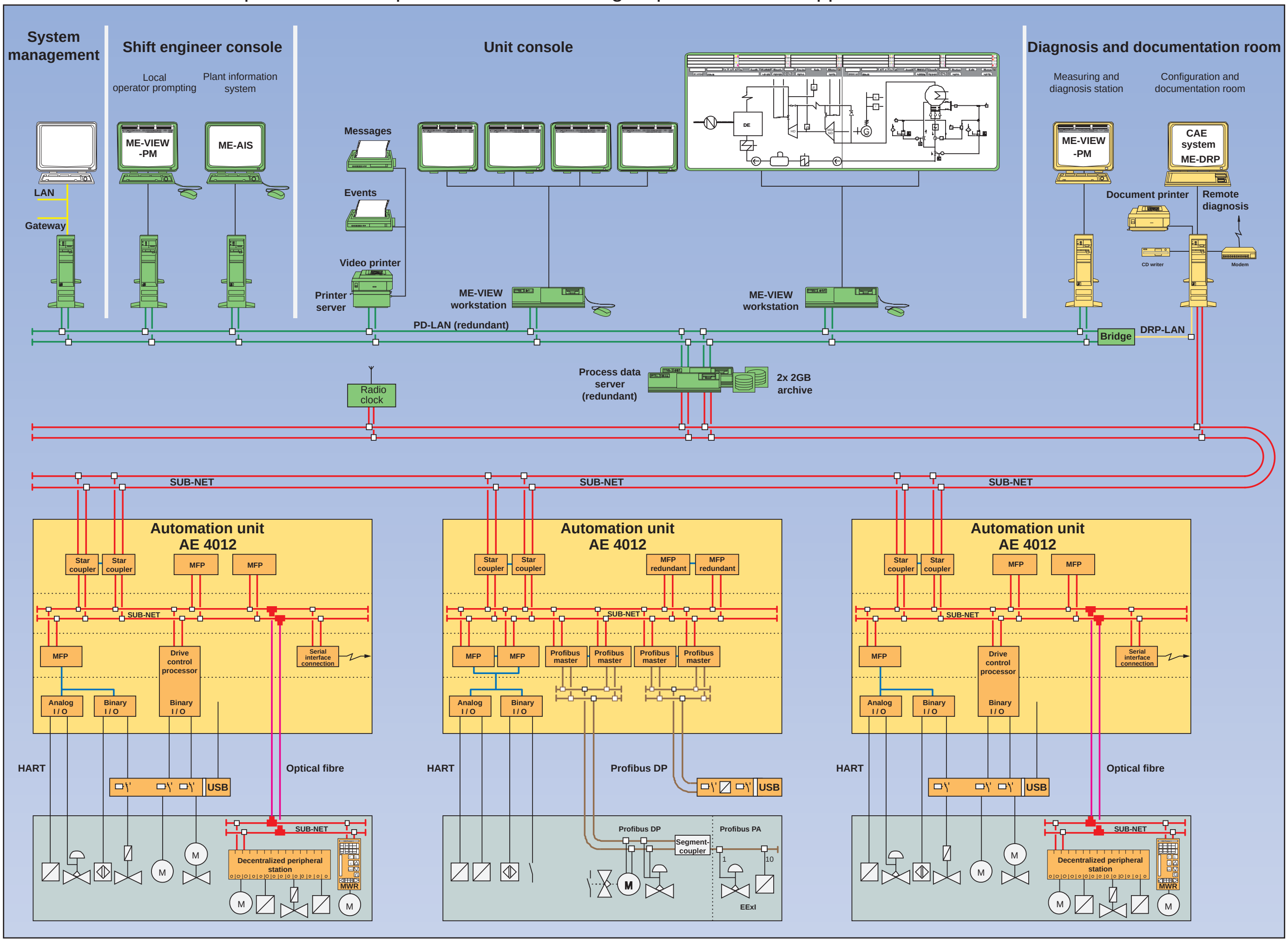
Today, economic production requires methods that are non-polluting and efficient in the use of our natural resources. In the power industry, environmentally acceptable energy production can only be achieved by a high level of process automation. Yet, automation alone is not enough. Equally important are high availability, performance and decentralization in power station control.

Our ME 4012 process control system meets these requirements and offers all functions required for the acquisition and conditioning of process data and the control, monitoring and optimization of plant processes. Yet, praxis-oriented solutions are based not only on a control system offering highly developed hardware technology and comprehensive firmware libraries, but also on extensive and detailed knowledge of all processes monitored and controlled by the system.

Therefore we are going to describe some applications of modern control algorithms that are standard procedures in today's ME 4012 process control applications.



Distributed architecture of the ME 4012 control system (DCS)

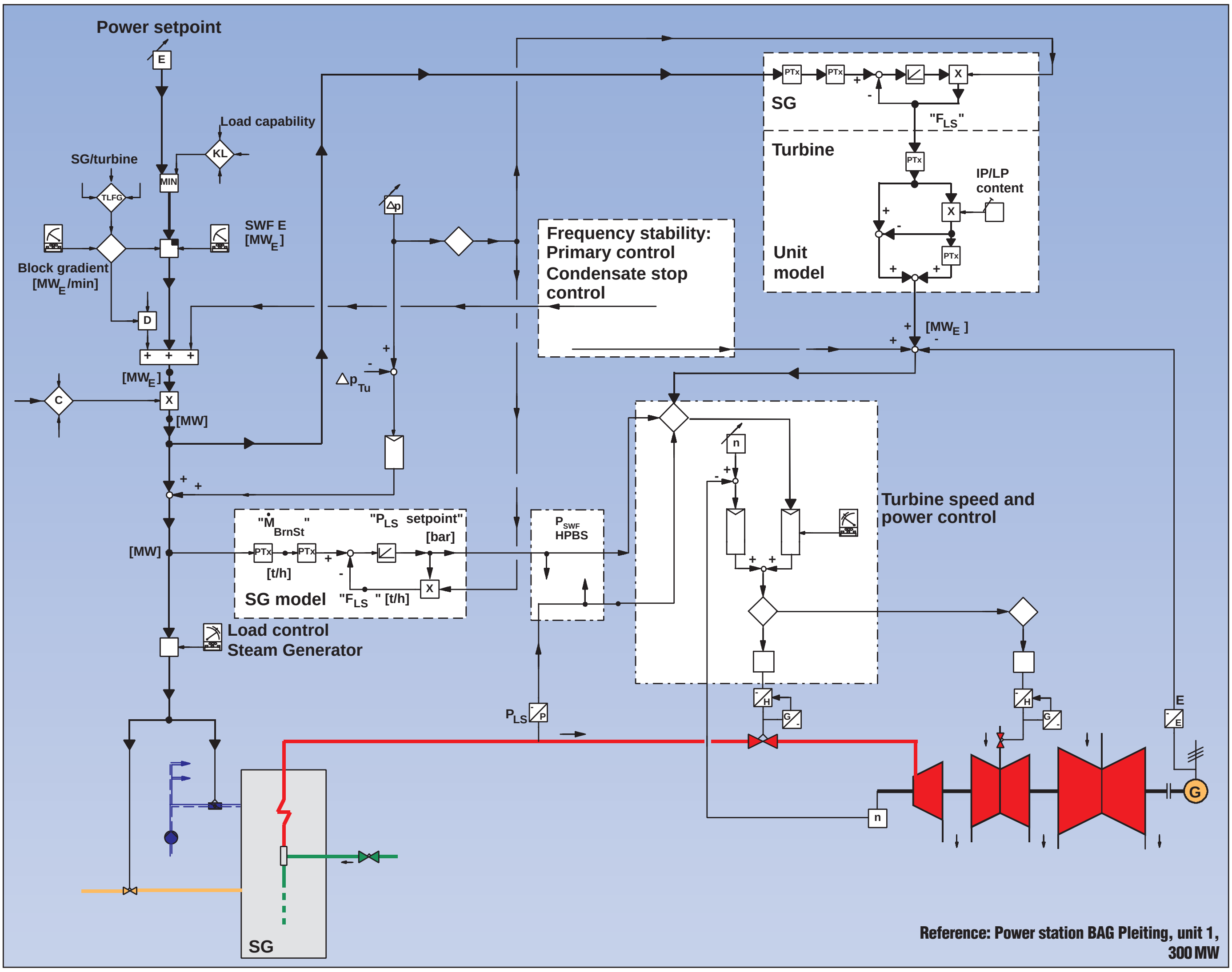
Let us start by briefly discussing the fields of application of modern control algorithms in today's steam generators and their auxiliary plants.

First, we will get an overview of the following topics:

- Unit model (smooth load control)
- Condensate stop control
- Calculation-guided control
- Multi-variable Fuzzy control
- Turbine speed and power control
- Observer-based state control

This will be followed by a detailed description of a control application that is of particular importance in modern power generation: The use of and experience gained with a Fuzzy control algorithm in firing power control in an incinerator plant.

Unit Model (Steam Generator and Turbine)

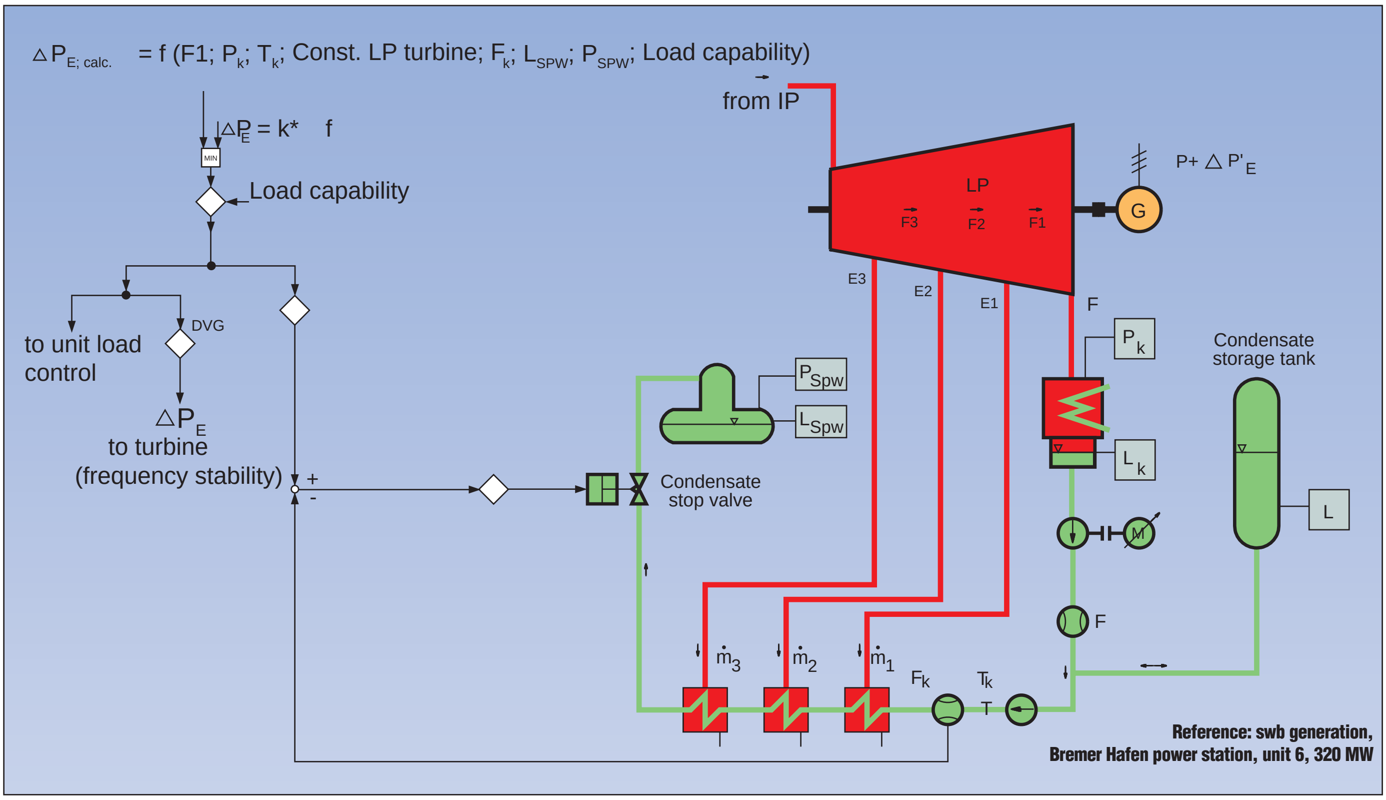


Structure of a modern unit model

Aim of the unit model application is a) the anticipation of the boiler and turbine output development and b) balancing the load by way of limiting the gradient and controlling the unit capacity (avoids agitated unit operation).

Large power station components may only be operated in line with their design-specific load. A setpoint control that is not optimally adjusted to the possible actual conditions will lead to unnecessary fluctuations in the control response and thus to unauthorized controller actions. This puts unnecessary strain on component materials and reduces plant efficiency.

If the time characteristics for the setpoint control of the essential components are derived on the basis of plant-specific parameters (e.g., load level setpoint gradient, storage capacity, etc.), the unit model can be used to implement a specific setpoint control of all large components which takes into account the actual process conditions. This will result in an optimal utilization of process dynamics and an increased overall efficiency at load variations. At the same time, untimely corrective actions in the control process – either too early or too late – caused by secondary setpoint control loops can be avoided.

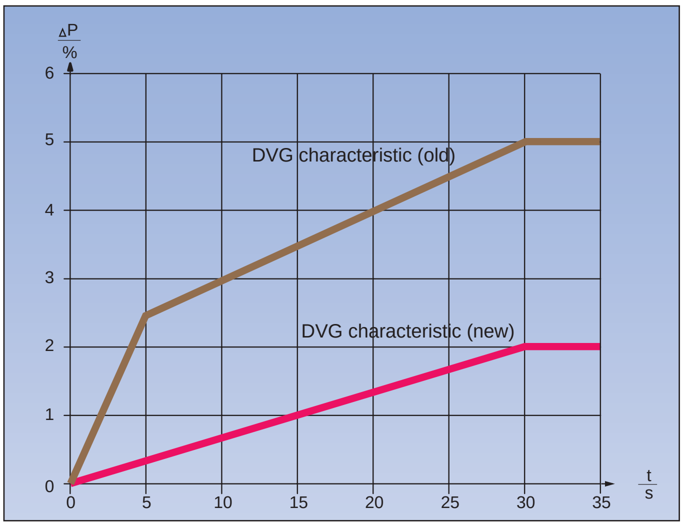


Condensate stop control

Condensate stop control forms the basis for the efficient generation of the active-power seconds reserve in accordance with the requirements laid down by the DVG guidelines, the former National Association of German Electricity Network Operators, now known as VDN. The reserve power fed into the grid for the purpose of maintaining frequency stability must be made available by the power unit within a specified period of time in line with the supply obligations agreed upon with the power distribution board. Condensate stop control is based on the principle that power can be generated by momentarily building up the condensate flow and expanding the diverted bleed steam via the turbine. In this situation, condensate built-up control replaces the normally employed method of throttling the admission valves and using the boiler as the steam accumulator. This way, an additional electric power in the range of 2 to 3.5% can be produced within a period of 30 seconds. By integrating the condensate stop control strategy in the steam generator unit model, the unit power setpoint and - consequently - the steam generator and turbine load control can readjust to accommodate the additionally required "spontaneous" reserve. As a result, the additionally drawn power can be followed-up in line with the dynamic process conditions and the condensate built-up can be resolved again. By using this method instead of throttling the turbine admission valves, efficiency can be increased by approximately 0.5 %. Moreover, the integration of the condensate stop control into the unit control model leads to a measurable stabilization of the steam generator control and increases the plant's operational flexibility. Many of the new regulations for connection conditions for power generation units laid down in the GridCode 2000 (Edition May 2000) have by now become binding requirements. (The GridCode2000 specifies the network and system rules for the German transmission system operators.). Thus, for instance, the primary control conditions for maintaining frequency stability for generating units ≥100 MW have been newly defined. Today, the generating unit must be capable of activating, within 30 s, at least ± 2 % of its nominal capacity for primary control at a quasi-steady frequency deviation of ± 200 mHz. The neutral zone must be below ±10 mHz.

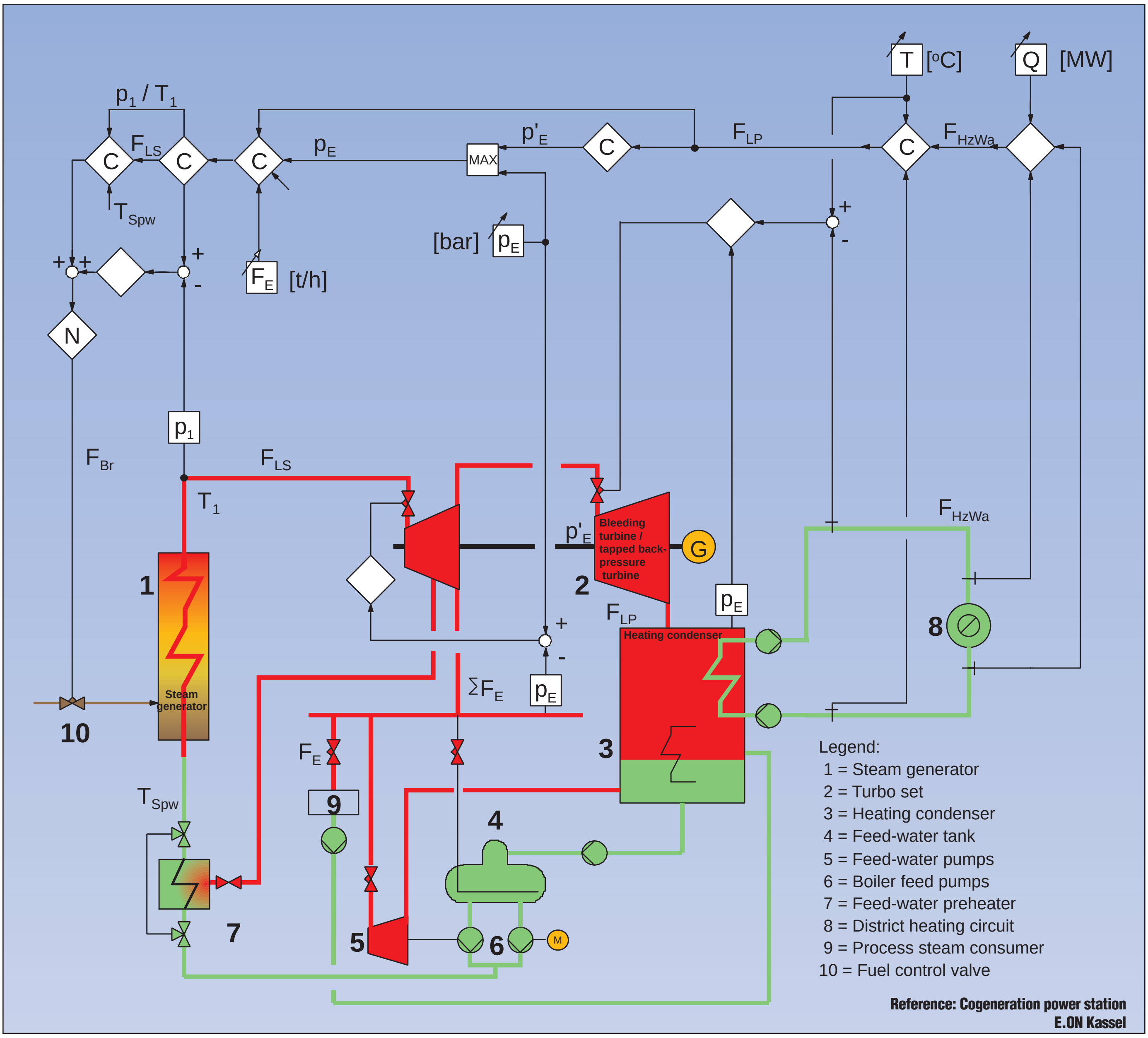
In order to successfully fulfil the above supply obligations on the basis of condensate stop control, the following must be implemented:

- Condensate control valve with quick-action operating mechanism
- Control volume of the feed water or cold condensate storage tank
- Unit control with frequency stability and condensate stop module



Former and new DVG requirements for thermal power stations concerning the active-power seconds reserve for the primary control of grid frequency stability

Calculation-guided Control



Heat supply from cogeneration based on calculation-guided closed-loop control

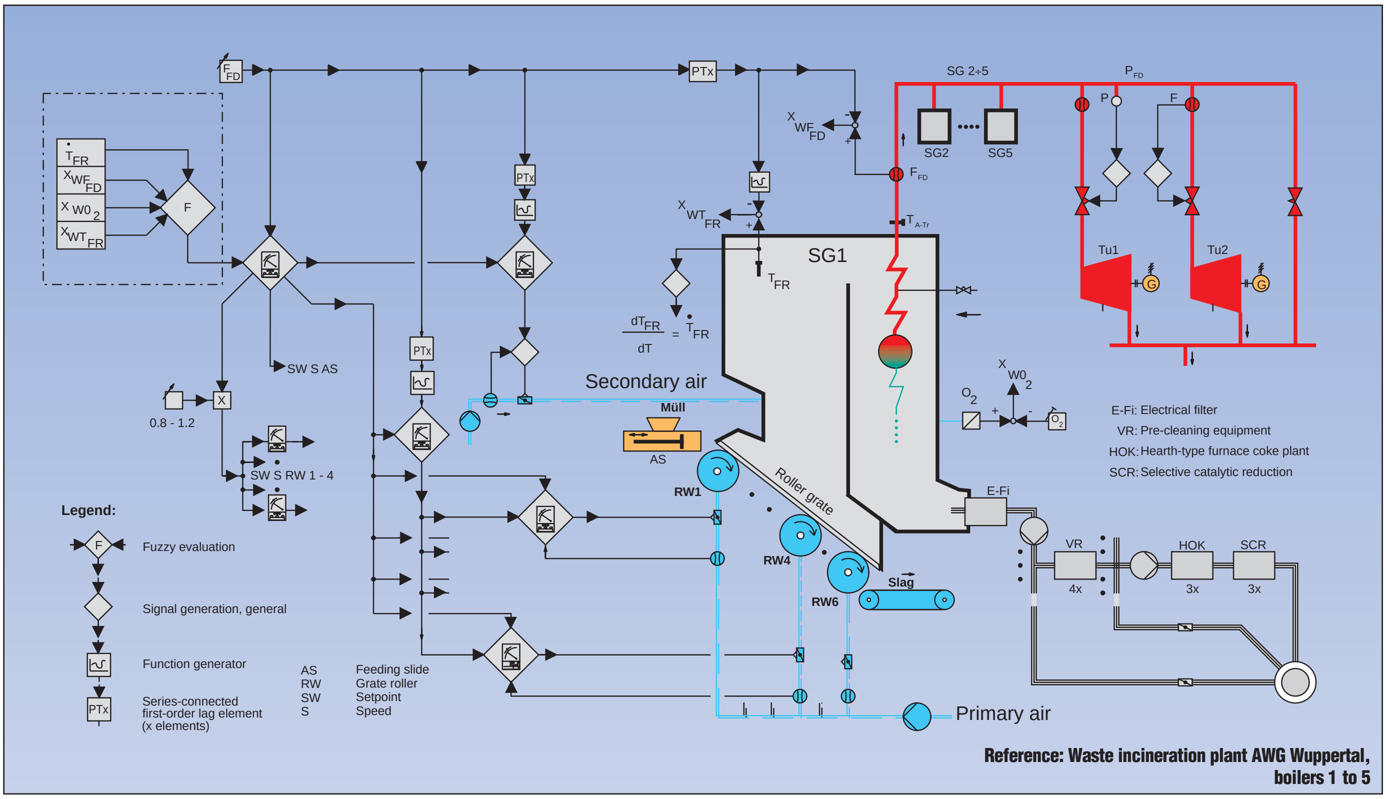
Calculation-guided closed-loop controls are primarily used in complex power station heat circuits where quite often contrasting tasks have to be solved, such as:

- Fast and opposite load variations at the consumer end, e.g., turbines / generator and district heating
- Slow increase of the steam generator output, e.g., fluid-bed firing of the steam generator

Using conventional closed-loop control circuits which are based on the principle of responding to control deviations, these tasks can only be solved with considerable efforts in the planning and commissioning phases. They also hinder a dynamic operation of the plant.

The unit model assigns parameters on the basis of the technological design specifications, and supplies reference input variables for all control loops of the meshed system - right up to the boiler load setpoint control. Model errors are corrected by the secondary setpoint controllers of all major process areas, such as LS floating pressure, turbine extraction pressure, heating condenser pressure.

Fuzzy Control Algorithms



Firing power control system with Fuzzy algorithm for a roller grate refuse boiler

Plant areas producing inconsistent process variable fluctuations which cannot be measured are difficult to control satisfactorily, even if complex control loops with a high degree of intermeshing and complex feedforward control are employed. The calorific value of refuse or brown coal, for example, cannot be determined satisfactorily due to the fluctuations in the composition of these fuels. The operation of incinerators in particular requires various fuelling parameters to be taken into account in order to achieve a high energy utilization factor. Such parameters would be, for instance, the furnace temperature range, the minimum retention time of the gaseous products at specific temperatures, air excess or starvation in the various burning zones, the quality of the steam parameters.

The method of multi-variable control based on a Fuzzy algorithm can be used for non-linear and linear processes. Reference setpoints are derived from the various actual values for all furnace-relevant control loops (e.g., control of the roller/ travelling grate speed, primary/secondary/tertiary air quantities, refuse feeding speed, backup firing).

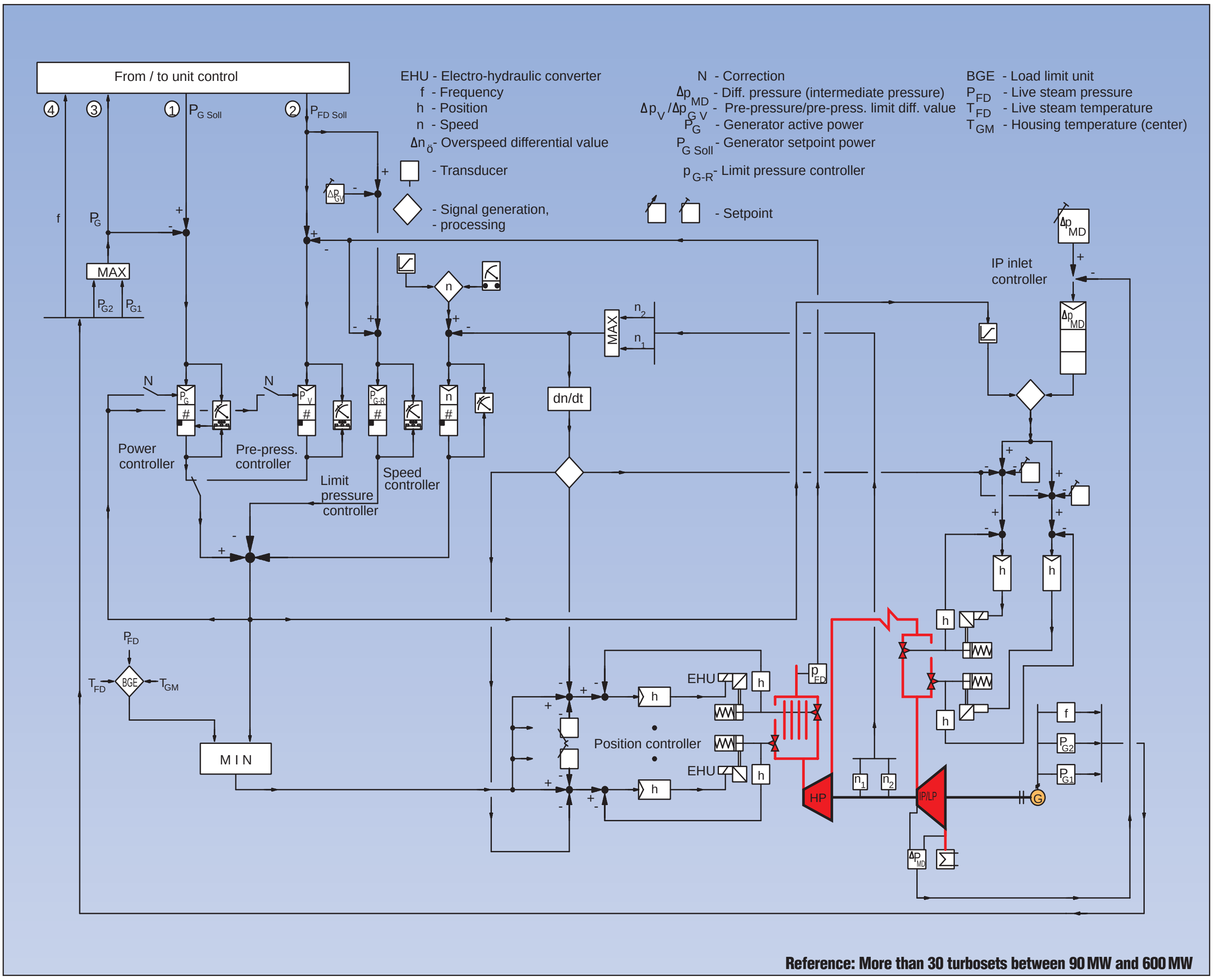
The implementation of multi-variable Fuzzy control resulted in the following operational improvements:

- Fully automatic operation of the firing power control taking into account all relevant closed-loop control circuits.
- Uniform output development and optimization of the refuse throughput rate, anticipating automatic firing/power control in line with the plant and component performance limits.
- Average deviation of the live steam quantity $<5\%$
- Higher refuse throughput rate per line
- Increased power production potential and efficiency
- Reduced flue gas losses
- Reduced variation load of the steam generator and thus less wear
- Reduced operation time of the supporting and pilot burners

The retrofitting of an ME 4012 or ME 400 processor module with the described Fuzzy control strategies and parallel-wire connection of all process data in existing process control systems will pay for itself in very short time.

Another application example of Fuzzy control is in FGD plant optimization where the deposition degree of the SO2 content in the flue gas is controlled. This is done by selecting and specifying the number of the absorber spraying levels in operation.

Steam Turbine Speed and Load Setpoint Control, Steam Turbine Protection



Turbine speed and load control

The development of digital turbine control as an integral part of the ME 4012 process control system has yielded a consistent control technology offering coherence in system hardware, documentation and communication while at the same time being particularly suited for applications with extremely high demands on turbine control criteria, such as:

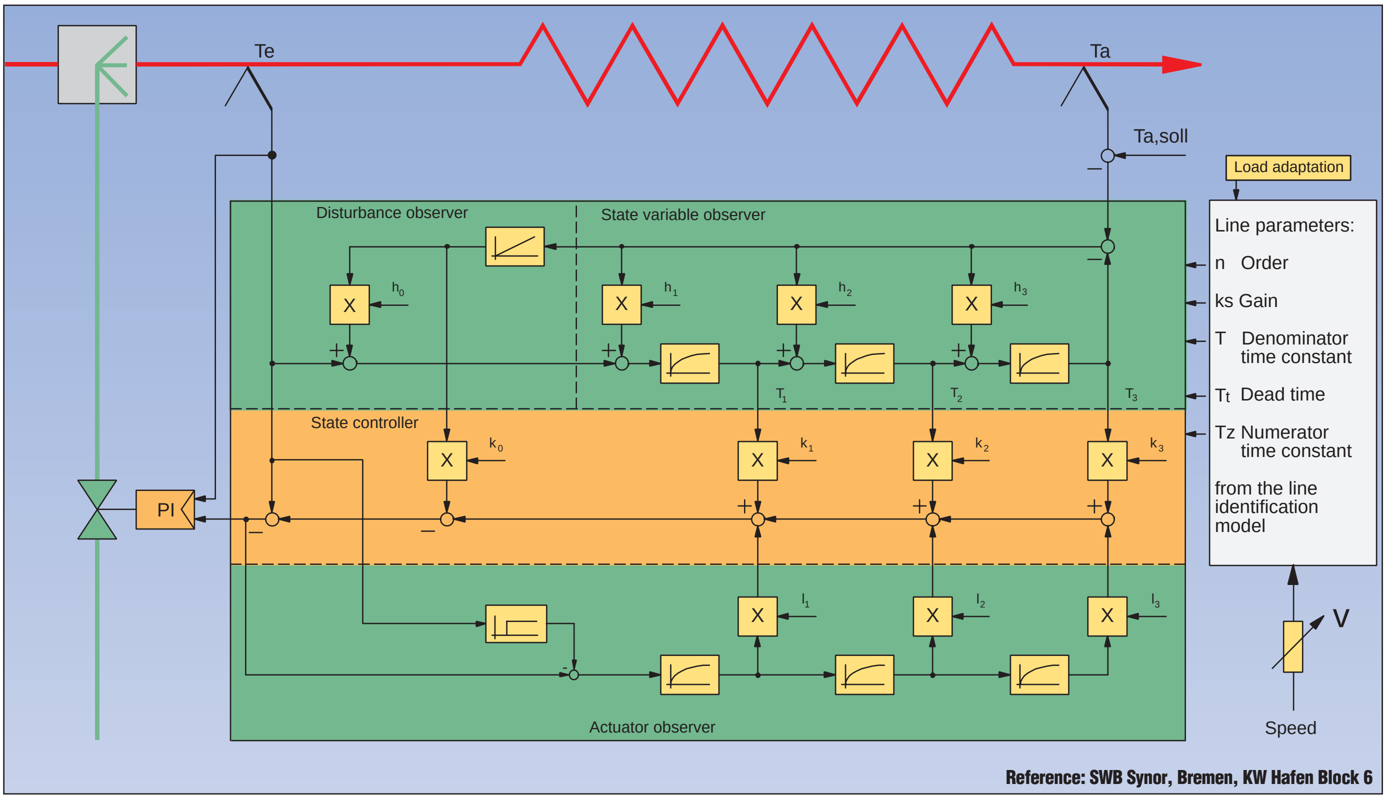
- Controller cycle time, e.g., for turbine speed control (<2 ms)
- Accuracy of measurement (0.004 % at nominal speed, corresponds to 2 mHz at a grid frequency of 50 Hz)
- ‚Safer (SIL3), reliable, fast and highly available signal and information processing for electronic turbine protection

Essential parts of the ME 4012 turbine control system are:

- Turbine controller (speed, load and live steam pressure)
- Frequency stability control acc. to DVG regulations
- Turbine Temperature and Load Reference Control Unit (TPR unit) for the calculation of temperature and load transients
- Open circuit turbine protection (material vibration, expansion, temperatures)
- Failsafe (SIL3) turbine protection (overspeed, generator and boiler protection, emergency shut-off)
- Turbine auxiliaries (measurement, drives, HP/IP bypass station control, function groups)
- Failsafe protection for HP and IP bypass stations
- Continuous self-test of open-circuit and failsafe protection systems
- Turbine control room (monitoring, operator control, message and alarm logging)
- Fault diagnosis, configuration and documentation at one central point
- Interfacing to station unit equipment via SUB-NET process bus, serial connection to third-party systems

Please refer to our application report ”Digital Turbine Control System” for further information.

Observer-based State Control



Observer-based state control, block diagram

The observer-based state controller is primarily used for higher-level processes with self-regulation, but can also be used for processes with dead time. An internal state observer analyses process- and plant-specific disturbances. The result of this evaluation is an important quantity in the genration of the actuating variable. Actuator non-linearity, system dead time, etc. are taken into acount by internal compensation circuits so that a persisting system deviation is avoided.

A program for the computer-aided determination of the transfer function derives the optimal values for all control parameters.

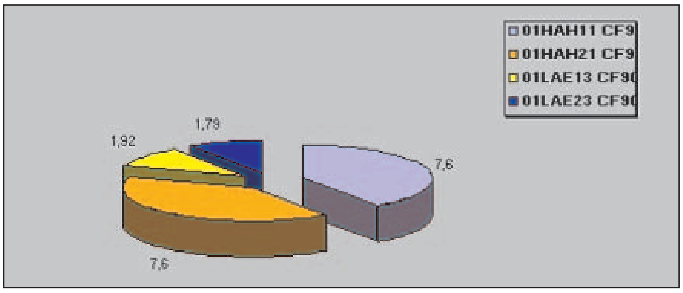
By connecting an online reference input variable the load level of the control parameters can be continuously adjusted.

The use of a state controller produces aperiodic and asymptotic damping of the controlled variable characteristics which in turn leads to smooth actuator operations of the injection water control valve and therefore a smooth response of the linked variables.

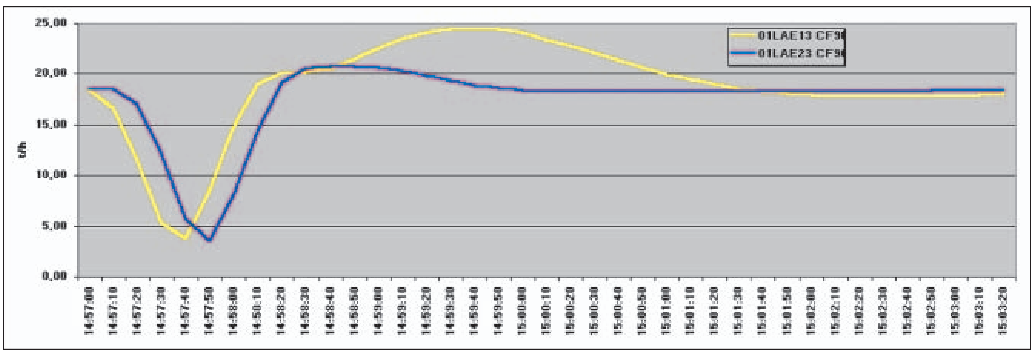
Interesting application examples of this control method are:

- Live steam temperature control
- Intermediate superheater temperature control
- Closed-loop control of the HP/IP bypass stations
- Control loops with highly load-dependent time constants and of higher system order

Please refer to our application report "State Controller with Observer" for further information.



Water-Steam balance [t], comparison PID versus State Control

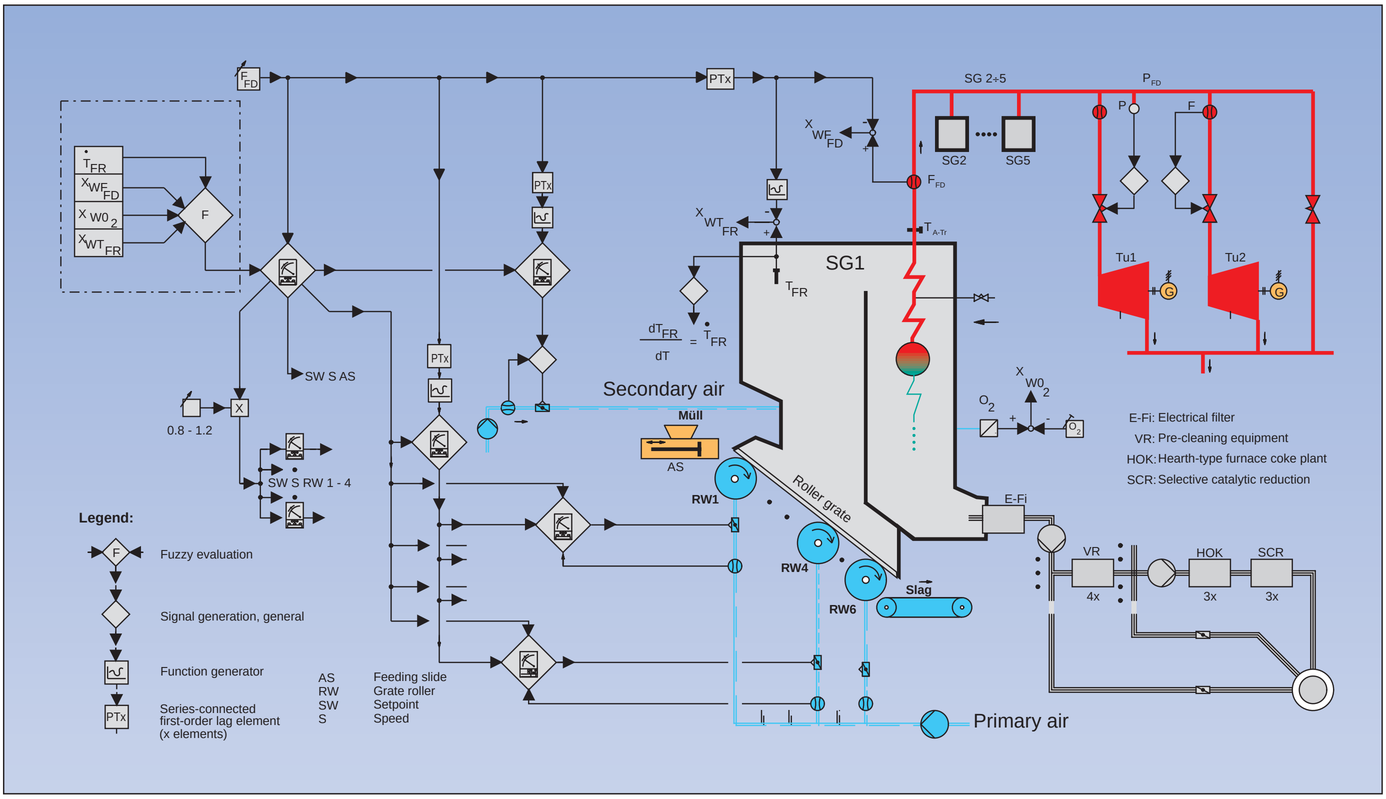


Injection water characteristics

Application Example ‘Firing Power Control’

Equipped with four boilers since 1976 the incinerator of AWG Wuppertal was initially designed for a combustion capacity of approximately 320,000 tons waste per annum based upon the average heat values at that time of 8,500 kJ/kg.
The plant was modernized in two steps and equipped with a fifth boiler in the year 1990. The plant’s flue gas cleaning system was modified to comply with the German emission standards (TAL86 specification).
Between 1992 and 1995, the flue gas cleaning system was enhanced by integrating a hearth-type furnace coke filter system and an SCR DENOX system in order to increase system performance in line with German air pollution laws (BImSchV 17).

At the same, time boilers 1 to 4 were replaced with a boiler type similar to that of the new boiler put into operation in 1991 in compliance with air pollution laws (BImSchV 17). The modernization of the plant also required the replacement of the electrical equipment and the process control and instrumentation system. The diagram below shows the current technological state of the plant which today has a combustion capacity of 385,000 t/a. The roller grate firing system has primary air injection that can be controlled for the individual zones and rotating nozzle bars for the injection of secondary air. Burners for the used coke disposal of the filter system were retrofitted. Owing to the higher degree of automation the number of personnel could be kept at the same level, even though the complexity of the plant had increased considerably.



New multi-variable load control based on Fuzzy algorithms

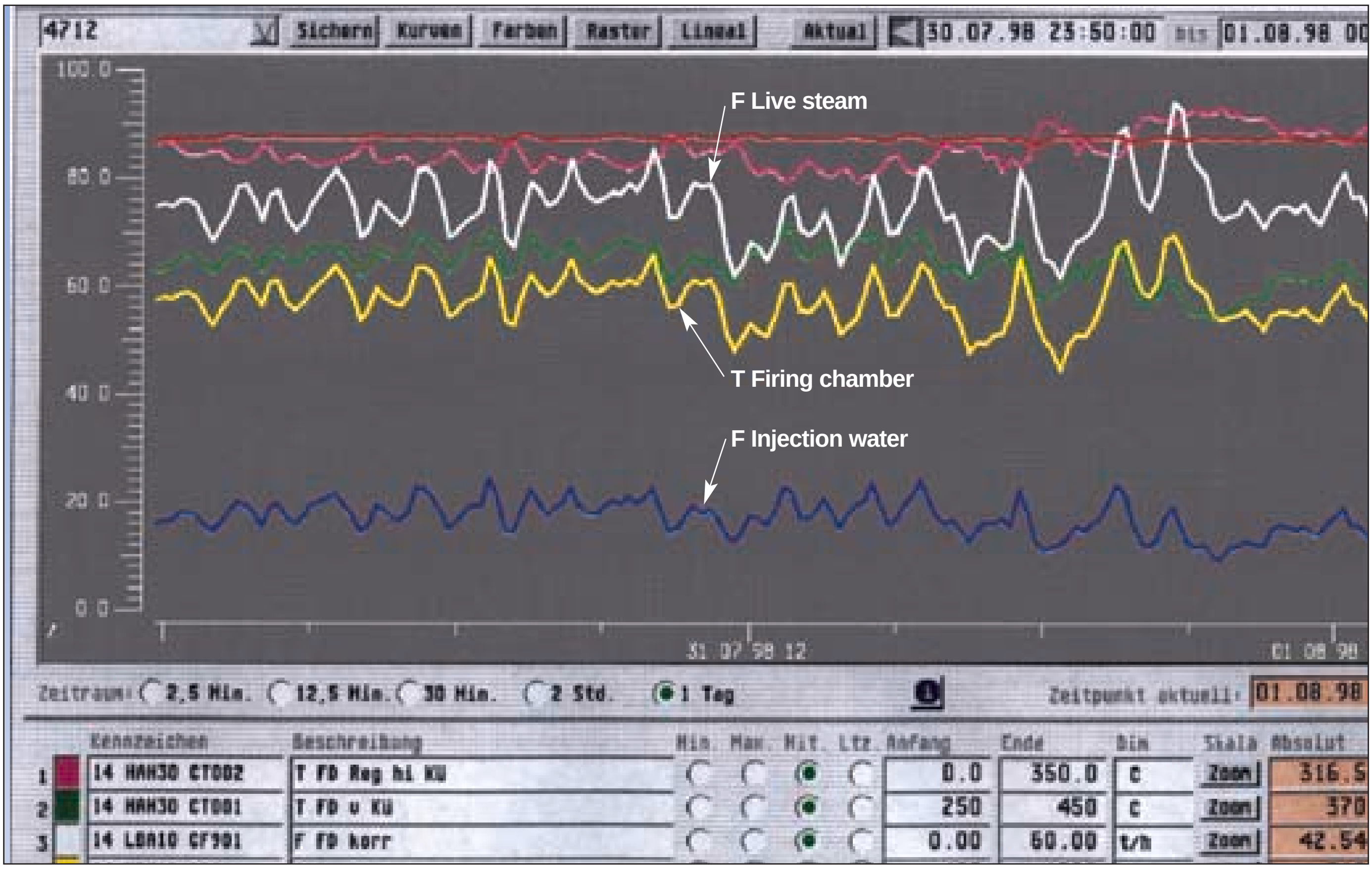
Operational Conditions of a Refuse-fired Furnace

The ancillary conditions of the refuse incineration process differ to a great extent from those of normal combustion plants, especially with regard to the conditioning and inhomogeneity of the fuel. Due to variations in the fuel mixture’s calorific value, density, humidity and ignitability in conjunction with an often discontinuous loading of the combustion chamber, it is nearly impossible to determine the optimal primary air distribution for the combustion process. This leads to spontaneous and erratic deviations in performance. Due to the inhomogeneity of the refuse to be burnt, it is not possible to define a steady relationship between the fuel and the air quantity for a discrete load level which restricts the use of conventional closed-loop control methods. The reproduction of a specific load level will always lead to different results. Even if a fixed load level could be determined, extensive system-inherent variations in the firing power supplied to the boiler would still remain. In contrast to oil and gas firing, and similar to coal firing, the slag output ”locked up” in the combustion chamber cannot be neglected.

All these effects can only be detected with a delay, i.e. after the output development has already taken place.

These general effects are experienced every day in the waste incineration plant of AWG Wuppertal with its five boilers (50 t/h max. per steam generator) connected to a common 30 bar live steam bar. Nevertheless, with very complex feedback control systems, prudently loading crane drivers and an attentive team of operators, the plant could be controlled quite satisfactorily under normal operating conditions.

The known changes in waste disposal regulations (e.g., traditional disposal areas can no longer be used, newly structured energy prices, continued operation of simple waste deposit sites) forced the waste management companies to react. In order to increase efficiency and make use of improved flue gas cleaning facilities, other types of refuse were considered for co-combustion. Although the extreme calorific value variations of these fuels of Hu_{min} = 8,200 kJ/kg to Hu_{max} = 20,400 kJ/kg were still within the design limits of the steam generator (SG), they were not within the limits of the process control software which is optimized to a calorific value bandwidth of about 9,000 kJ/kg to 16,000 kJ/kg. The peaks in the performance characteristics due to the extreme variations in the calorific value could not be predicted in time. An immediate consequence of the combustion of these refuse materials was that due to the sporadically large variations in the steam quantity (see the following figure) the live steam quantity setpoint of the individual boilers had to be lowered to be able to operate the turbine (which is hydraulically in pre-pressure control) within the control range even at extreme steam variations. This led to a reduced steam production so that less steam was available for the generation of electricity and for district heating. It also reduced the refuse throughput for incineration and increased the use of the supporting burners.



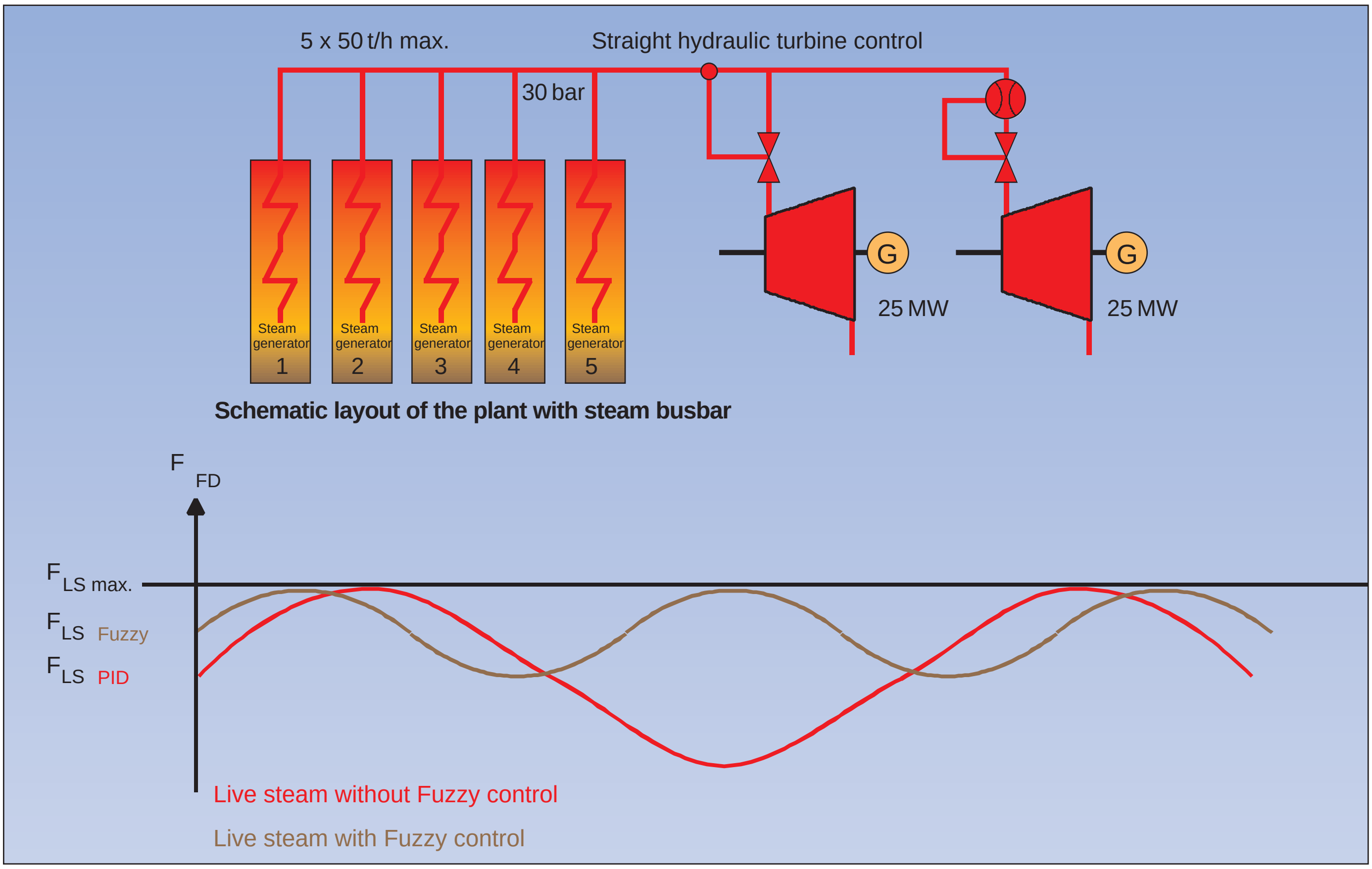
Daily characteristics of the operation parameters prior to the change of the process control and instrumentation system to multi-variable load control

The result in concrete numbers under normal operating conditions:

- The live steam quantity is reduced by approx. 10 %
- The current output is reduced by approx. 19 GWh for a projected 8,000 h/a
- The theoretical refuse throughput rate is reduced by 30,000 t/a
- Use of the light oil backup burners

A total loss of turnover of approx. 3,750,000 EURO per year.

Another indirect consequence was the much higher thermal variation load of the steam generator.



Reduction of the live steam quantity variations using firing power control based on a Fuzzy algorithm

Combining the Knowledge of the System Experts

The objective for rectifying the quite substantial operational losses and avoiding a possible long-term damage to the plant was therefore evident:

- Uniform output development despite inhomogeneous fuels
- No modifications to the existing mechanical and measuring equipment

In order to find an appropriate solution to these problems, the following basic measures were agreed upon in close cooperation with the supplier of the existing process control and instrumentation system:

- The new operational data were compared with the previous data acquired for normal plant operation and during the commissioning stage and analyzed.
- The long-term observations of the control room operators, shift managers, works managers and boiler manufacturers were analyzed.

The analysis of this information indicated that certain multi-variable process characteristics show a similar behaviour, that is, they roughly follow a set pattern which can be produced.

Therefore it was decided to pick out the critical information and archive these specific measuring values, such as:

- The combustion chamber temperature
- The rate of change of the combustion chamber temperature
- The live steam and feed water quantity
- The O_2 content of the flue gas
- The Δp characteristics of the grate roller primary air
- The individual primary air and secondary air quantities

Fortunately some of the values, such as the rate of change of the firing chamber temperature and the O_2 content, clearly indicated the possibility of anticipating a change in the output development.

Apart from the empirical and technological correlations, the following general conclusions could be derived from the analysis of the recorded measuring values:

- The existing conditions require that the measurable values that first indicate an unwanted output development (+/-) are taken into account.
- This forecasting information must always be evaluated in conjunction with other important variables (multi-variable grouping).

Although the possibilities of multi-variable monitoring were by no means exhausted with these analysis results, the knowledge derived from these correlations was sufficient to achieve the primary target, a uniform output development.

Other technological correlations beside those of multi-variable monitoring were examined with the following results:

- The closed-loop control circuits that are considerably affected by the unwanted output development, e.g., the superheater temperature control circuit, must be isolated more distinctively.
- The system-specific load variation effect due to the discontinuous feeding of waste must be reduced as much as possible.

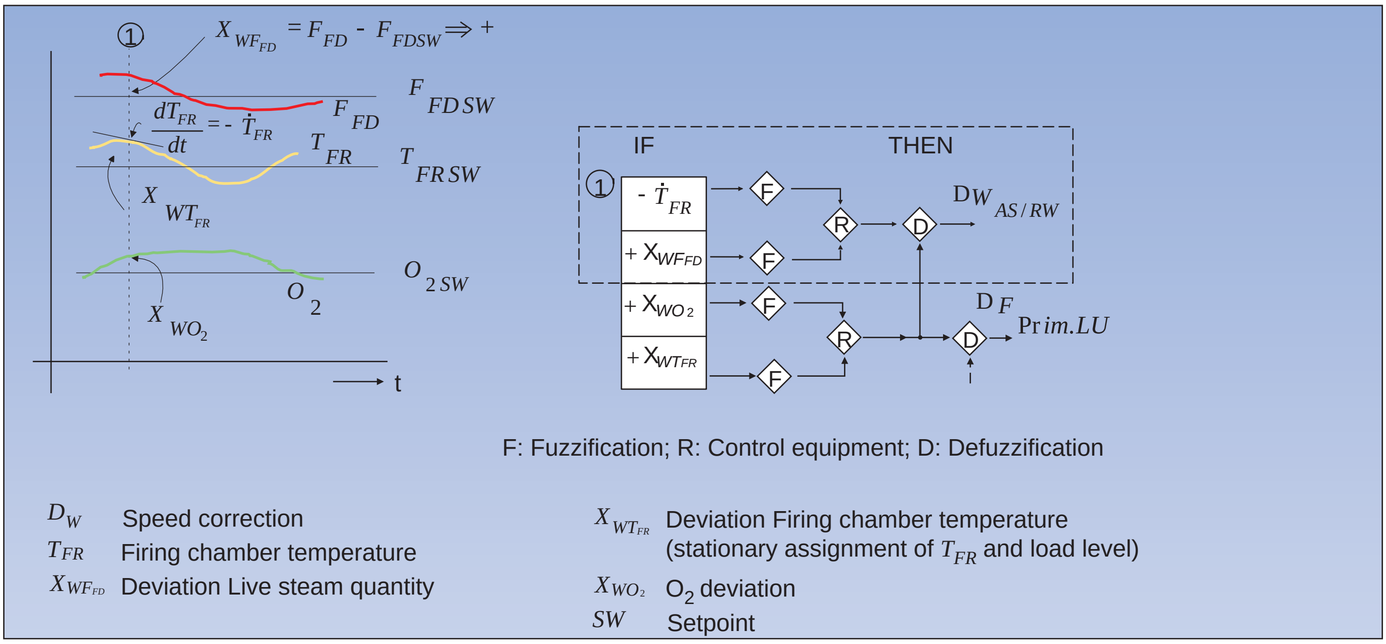
Nearly all of the technological facts and correlations listed above pointed to multi-variable closed-loop control which could be implemented in a most comfortable way using the existing Fuzzy control function blocks of the ME 4012 process control system's firmware library.

Discrete refuse, primary air and secondary air mass flow values are allocated to every load level. The magnitude of these values is related to the average refuse density and calorific value. The parameters for the refuse feeder positioning rates, roller grates and stated air quantities derived from these values on the basis of conventional process correlations are adapted to the current refuse quality by means of multi-variable compensating control based on Fuzzy logic.

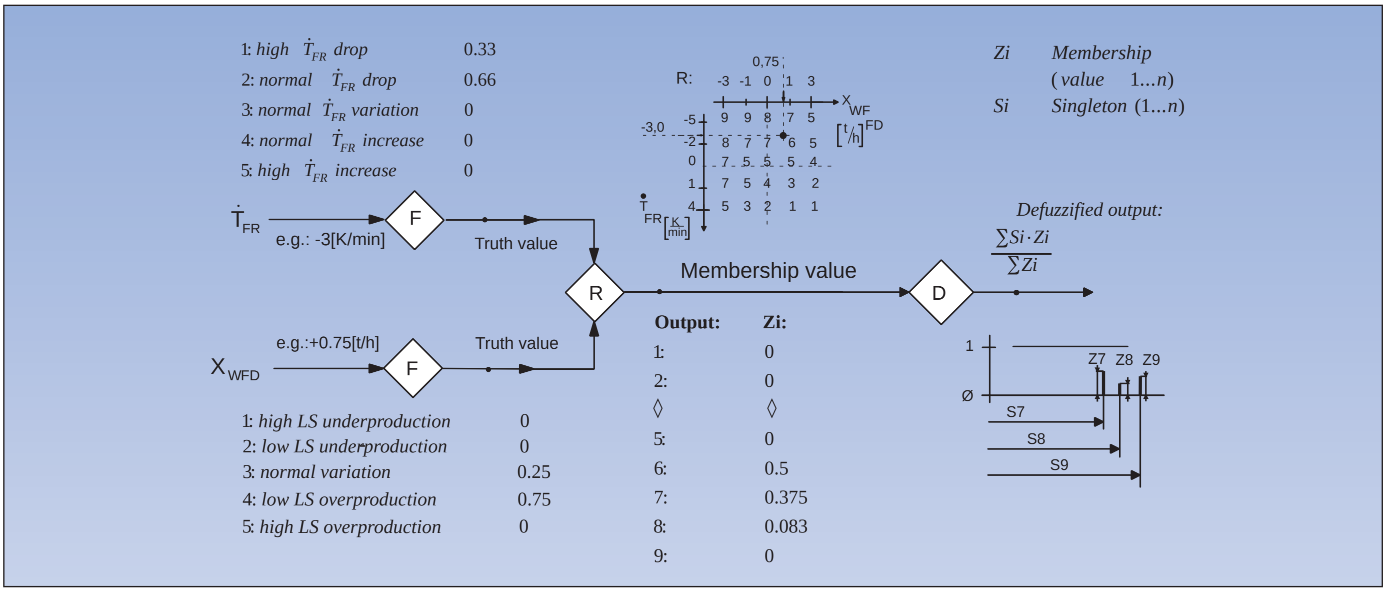
The grouping of the corrective values in a Fuzzy evaluation represents the non-existing direct measurement of the output development directly above the roller grates (see the following 3 figures).

- $\dot{T}_{FCh}\,[K/min]$ — Rate of change of the firing chamber temperature (dT_{FCh}/dt)
- $X_W F_{LS}\,[t/h]$ — System deviation of the live steam quantity
- $X_W O_2\,[\%]$ — System deviation of the oxygen contents
- $X_W T_{FCh}\,[K]$ — System deviation of the live steam temperature
- $F_{PrimAir}\,[Nm^3/h]$ — Primary air quantity
- $F_{SecAir}\,[Nm^3/h]$ — Secondary air quantity
- $\Delta P_{Roller\ grate}\,[mbar]$ — Primary air differential pressure above the roller grates

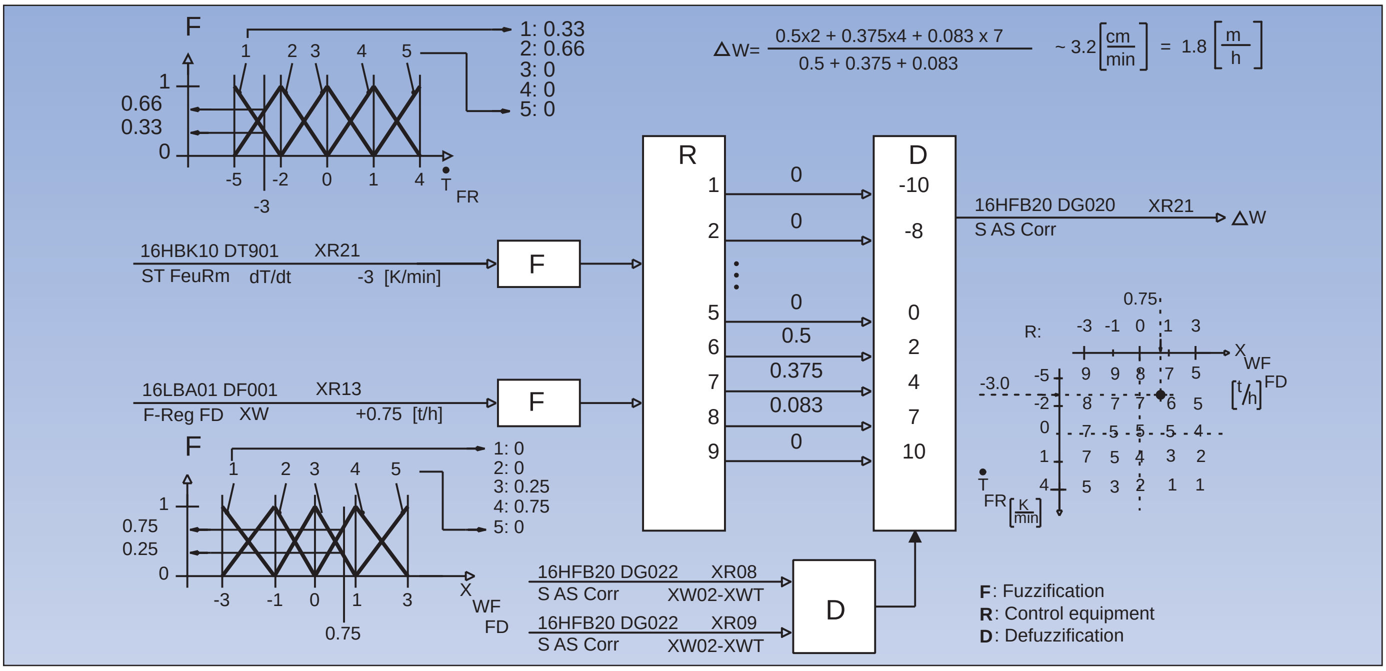
Due to the fact that basic Fuzzy elements do not have their own time functions, these are replaced primarily via the input variable or the rates of change of the other Fuzzy input variables taking into account the specific process conditions.



IF-THEN (Fuzzy) rules are derived from the combined process characteristics



Fuzzy block diagram (Fuzzification – Control equipment – Defuzzification)



Functional diagram with parameter assignment possibilities

New Load Control Strategy

After the analysis of the plant-specific expert knowledge and the combined measuring values from the special archive, the actions on the actuator commands were specified and the new knowledge became an integrated part of the existing process control and instrumentation system.

The upper diagram on page 14 illustrates how IF-THEN Fuzzy rules are derived from on the basis of real process values:

IF at a specific point in time (e.g., time 1), the values from principally repeatable process characteristics take on the following magnitudes:

$\dot{T}_{FCh} \approx -3.0\ [K/min]$	Rate of change of the firing chamber temperature (dT_{FCh}/dt)
$X_W F_{LS} \approx +0.75\ [t/h]$	System deviation of the live steam quantity
$X_W O_2 \approx +0.6\ [\%]$	System deviation of the oxygen content
$X_W T_{FCh} \approx +7.5\ [K]$	System deviation of the live steam temperature

THEN the compensation speed of the refuse feeder or roller grates is increased by $\Delta W \approx 3.0\ [cm/min] = 1.8\ [m/h]$. At this point this happens without primary air compensation as the $X_W O_2$ deviation is still within acceptable limits.

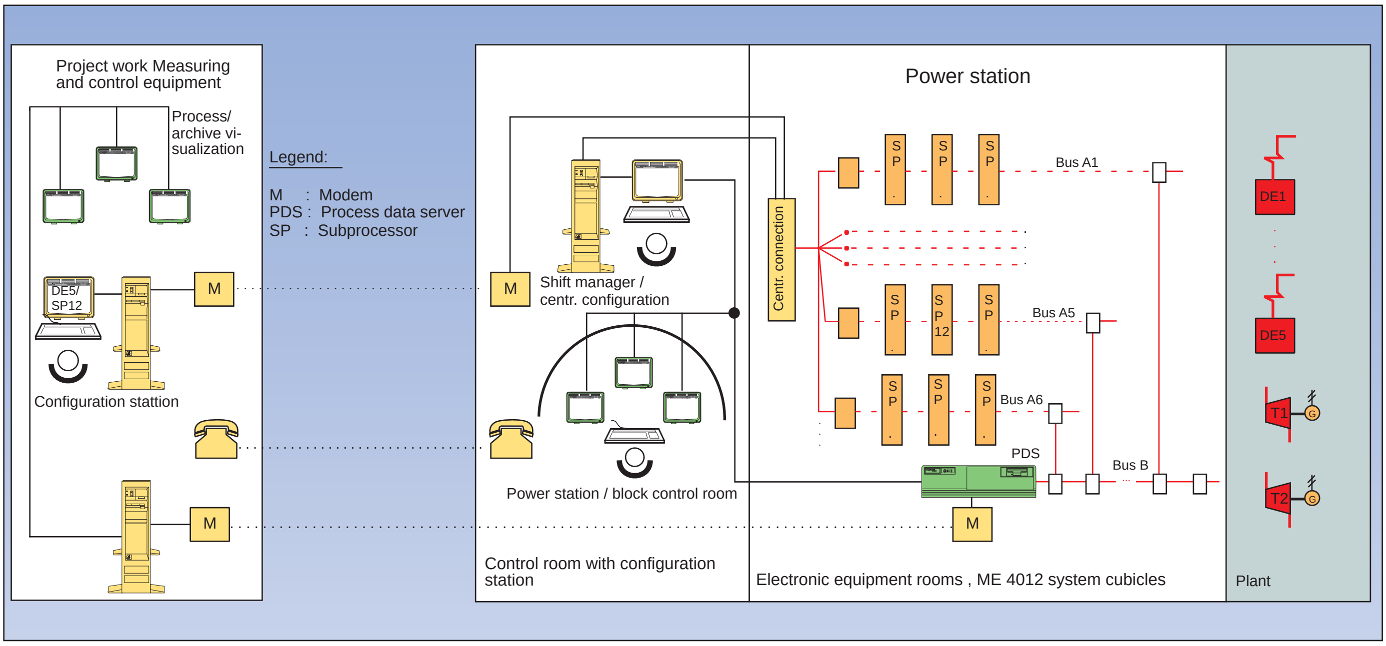
In practice you start with the signal pairs that have the broadest affect on the process, in our case this is the pair $\dot{T}_{FR}$ and $X_W F_{FD}$ followed by the pair $X_W O_2$ and $X_W T_{FR}$. This can be continued with other useful signal pairs if required.

Decisive for the selection of these signals is of course the aim that is to be achieved. The stabilization of the load control required the use of corrective variables that would indicate the correct tendency as early as possible. The observations showed that the signals $\dot{T}_{FCh}$ and $X_W O_2$ have very effective forecasting characteristics and must therefore receive a high rating in the matrix evaluation (see figure on page 15) of the linguistic variables.

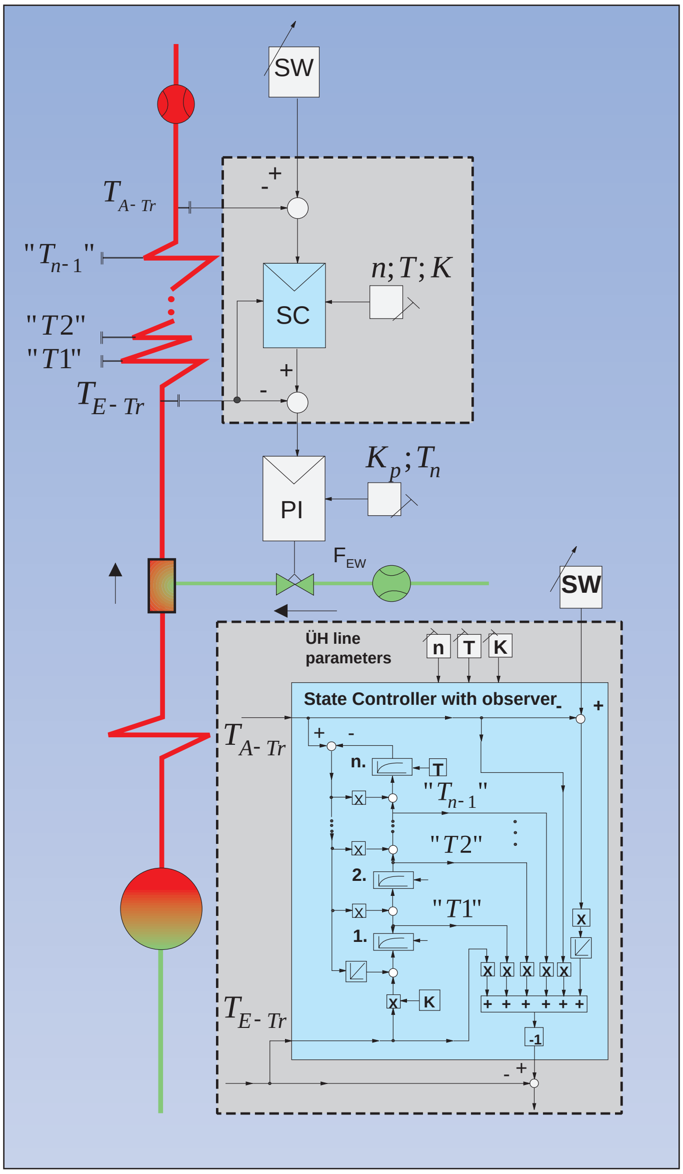
It requires of course expert knowledge and experience to be able to select and evaluate the signals suitable for Fuzzy control. Fuzzy control is by no means a magic formula that provides an instantaneous solution for every single problem. Fuzzy control can be seen as a possibility to represent the derived theoretical and empirical knowledge in schematic form and perform a mathematically exact analysis of this knowledge. Fuzzy logic is relatively easy to comprehend by both users and process control system engineers.

The measuring points of the signals actually used for this project's Fuzzy logic control system are illustrated in the figure on page 11.

In order to test the new algorithms derived in this way, they were implemented in the form of a pilot control circuit and loaded into an additional bus-connected automation unit for one of the boilers. To rule out uncontrolled interactions on the running operation, only the input variables were connected actively. The resulting actuator commands remained offline for the time being and were recorded only.



Online planning and remote commissioning (remote data transmission)



State controller at the final superheater

Long-term Remote Monitoring of the Pilot Circuit

The complexity of the technological processes and process control and instrumentation systems in today's industrial plants is steadily increasing. At the same time, the times for planning, manufacturing, installation and commissioning are reduced. Sufficient time for the optimization of a plant is often not provided.

If, as in this project, the normal commissioning stage has long been concluded for all boilers and the plant is in operation, the possibilities for selective load changes necessary for an optimal adjustment of such a control circuit are very limited. In this case, the commissioning engineer would be forced to wait for those operating stages that coincidentally offer the right conditions. To avoid this it was decided to set up remote data transmission.

It was now possible to observe and record the current data of the input variables and actuating variable outputs comfortably at the workstation in the office of the commissioning engineer. Using the same communication path, the results derived from this information were then integrated in the configuration and parameter assignment of the local automation unit. Owing to the selective connections to the process, interference with the running operation could be completely ruled out. The expenditure in time could be minimized by analyzing only the interesting phases of operation in the archive during normal office hours. Details on specific operating conditions could be asked for over the telephone. In the opposite direction, the personnel used the phone to inform the commissioning engineer about short-term changes in the running operation or specific operating conditions.

This implementation of remote monitoring and configuration and the analysis of the archived data opened the possibility for a thorough and cost-effective examination of the ambiguous multi-variable relations, not always to the full technological depth due to the limited number of measuring points, but with sufficient practical plausibility.

During the optimization stage the effects of the remaining inhomogeneous output characteristics on the superheater outlet temperature could be clearly recognized. These effects are further increased due to the fact that no additional controllable superheater is installed towards the final superheater - the existing controllable superheater must deal with all fluctuations in the superheater lines.

Furthermore, only the outlet temperature with the highest delay measured at the end of the line is available for closed-loop control. The effect of the fluctuating injection water quantities on the live steam overall quantity thus represents just another disturbing factor for the load control circuit (which is a very delicately operating system as it is).

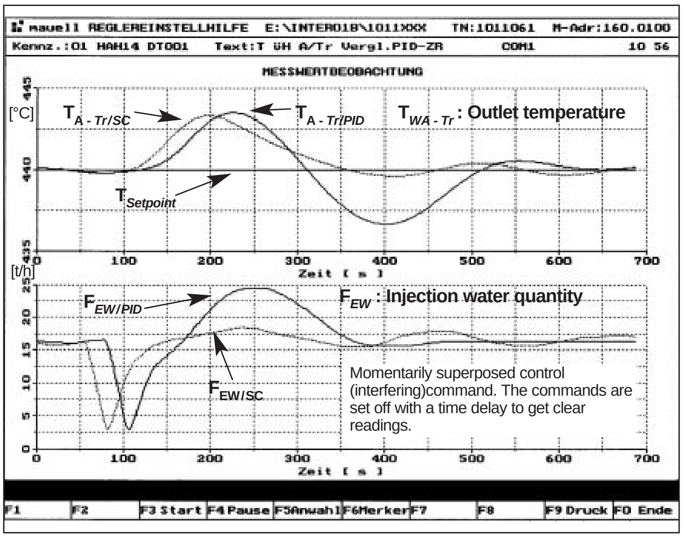
”Breaking up” these correlations required no Fuzzy logic. The well-known but still undervalued state controller with observer represented itself as an adequate solution. The control function of this device, which takes into account the effect of the superheater’s outlet temperature on the known superheater processes, is quite sufficient. The effect of the injection water fluctuations on the live steam overall quantity could be restrained. A new measured variable was not required. The corresponding control circuit and effects are illustrated in the diagrams below.

The discontinuous waste flow (feeding slide) could be changed to a quasi-continuous flow through synchronization with the first grate roller and by controlling the grate rollers’ differential speed. Moreover, the flow rate-oriented differential pressure of the primary air above the grate rollers can be used for the additional monitoring and correction of the waste bed density.

After several weeks of passive parallel operation of the pilot circuit, the conditions were such that the actuator outputs could be connected. Then it took only a few more minor corrections to complete the control circuit.

The achieved improvements had to be verified by means of test runs.

Finally, the multi-variable Fuzzy control of the firing power control system was integrated in one of the existing AE4012 automation units. The additional automation unit installed for the optimization process was removed.



Comparison of a PID+PI and SC+PI cascade under the same operating and interfering conditions (due to the state controller’s anticipating character the overmodulation of the ”F_{EW} fluctuation” is restricted)

Analysis and Operational Results

The implemented changes were tested for their efficiency in the daily operation of the plant by means of a verification program. The program's test criteria were specified before the modifications were put into practice.

Live Steam Control Quality

In test runs over two weeks the operational data of the not yet modified "old" boilers were compared with those of the first boiler with Fuzzy control. The results are as follows:

Without Fuzzy control $|\overline{X_W}|$ = 2.75 to 4.05 t/h

With Fuzzy control $|\overline{X_W}|$ = 1.67 t/h

These are the automatically computed results. A manual evaluation produced an even better result of an additional 0.3 t/h because longer disturbances, like for example the failure of grate roller, were taken into account.

Average of the 10 Highest Peaks of the Weekly Live Steam Quantities

Without Fuzzy control $|\overline{X_W}|_{max}$ = 7.9 to 9.8 t/h

With Fuzzy control $|\overline{X_W}|_{max}$ = 5.6 t/h

Due to the improved adaptation of the waste bed, grate roller speed and air quantities to the current waste conditions and, as a result, the improved uniformity in temperature distribution, the thermal cycling effects on the thick-walled parts of the plant could be considerably reduced (see figures on pages 12 and 18). However, more frequent actuating movements of the servo drives involved must be accepted.

The set goal was achieved. The production of electric energy and of steam for district heating, and therefore the combustion throughput rate, was increased to reach the initially higher level and even exceeded it, and this despite of the difficult conditions.

And it should be noted that the possibilities of this new control approach are by no means exhausted yet as additional multi-variable pairs can be used to further improve control efficiency.

Conclusions

The extreme-waste problem required a new assessment of the operational results:

- For complex, non-linear processes that cannot be clearly described with direct process variables, Fuzzy control function elements represent a very suitable solution.
  The possibility of combining the theoretical and empirical knowledge of the correlations between input and output variables, in conjunction with the evaluation of the uncertain logic from 0.0 to 1.0, allows building a stable multi-variable control system on a broad basis.
- System experts must gain some experience with the operating conditions of the plant before their knowledge (in contrast to the conventional knowledge from technical literature) can be optimally integrated in the Fuzzy control system.
- The use of "more intelligent" function elements, such as Fuzzy control and state controllers with observer, generally does not require additional sensors or actuators. The integration of such additional components into the existing system would have required extensive constructional modifications to the system.

Daily characteristic of the operational parameters after the modification to multi-variable load control

- Modern process control and instrumentation systems allow non-interacting testing of a variety of functions while the plant is running. In conjunction with the monitoring and storage facilities available, the operational results can be analyzed very comfortably and cost-effectively.
- The personnel requirements for the fine adjustment of the control and closed-loop control functions are high due to the necessary observation of the plant's operation conditions over a longer period of time. Remote monitoring and parameter assignment can help to considerably reduce personnel costs.

It should be noted here that the measures of improvement described above are not restricted to plants with new process control and instrumentation systems. As new actuators and sensors are seldom necessary, encapsulated modern process control functions can be relatively easily integrated into existing process control and instrumentation systems.

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