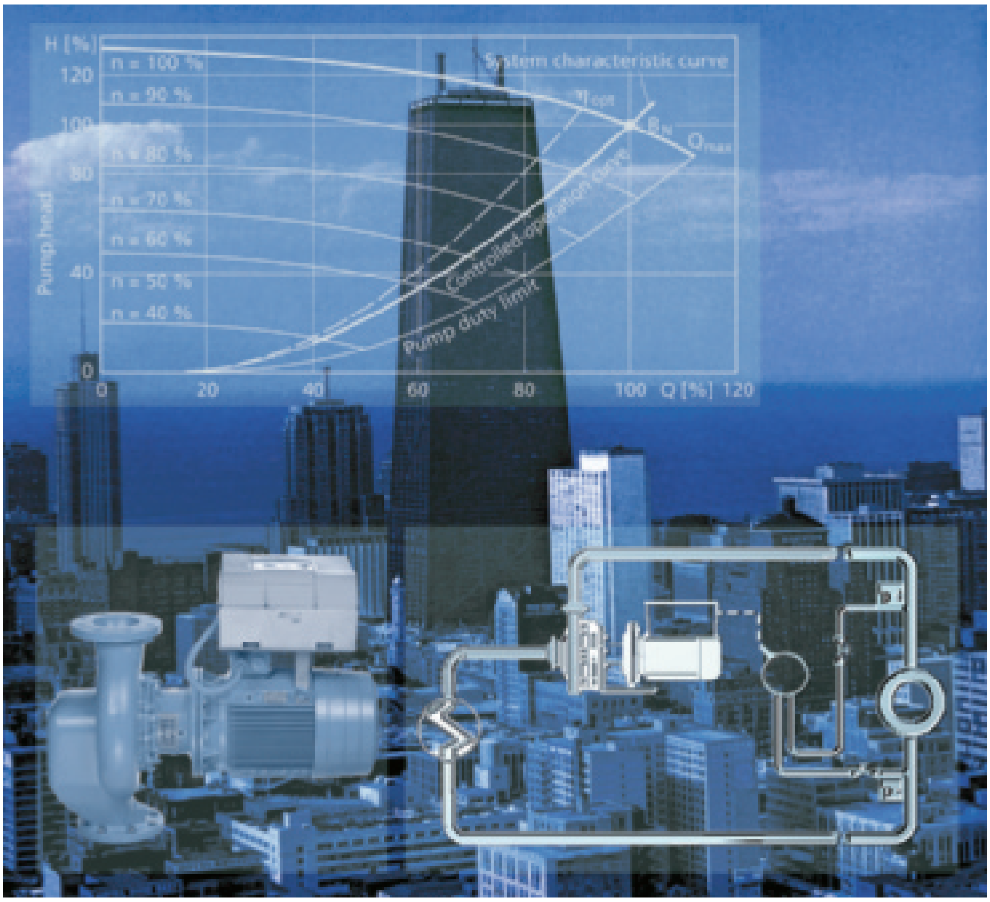
KSB Know-how, Volume 4

Pump Control / System Automation



KSB

Pump Control / System Automation

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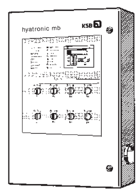
KSB Control Concepts

- Pumps with integrated control
  - Glandless pumps
    - Riotronic S / Riotronic ECO
    - Riotec / Riotec Z
    - Rio-Eco / Rio-Eco Z
  - Glanded pumps
    - Etaline PumpDrive / Etaline Z PumpDrive
- Pump control systems
  - hyatronic mb



Technical Data

Riotronic S

- Q up to 3.5 m³/h, 1.0 l/s
- H up to 6 m
- T + 20 °C to + 110 °C

Riotronic ECO

- Q up to 2.5 m³/h, 0.7 l/s
- H up to 5 m
- T + 15 °C to + 110 °C

Technical Data

Riotec

- Q up to 60 m³/h, 17 l/s
- H up to 10 m
- T + 20 °C to + 110 °C

Riotec Z

- Q up to 90 m³/h, 25 l/s
- H up to 10 m
- T + 20 °C to + 110 °C

Technical Data

Rio-Eco

- Q up to 60 m³/h, 16,7 l/s
- H up to 13 m
- T – 10 °C to + 110 °C

Rio-Eco Z

- Q up to 108 m³/h, 30 l/s
- H up to 13 m
- T – 10 °C to + 110 °C

Technical Data

Etaline PumpDrive

- Q up to 788 m³/h, 219 l/s
- H up to 100 m
- T – 10 °C to + 110 °C
- p_d up to 16 bar

Etaline Z PumpDrive

- Q up to 479 m³/h, 133 l/s
- H up to 76 m
- T – 10 °C to + 110 °C
- p_d up to 16 bar

Technical Data

hyatronic mb

- 1-8 pumps, modular layout
- Up to two frequency inverters with full permutation
- For motor powers up to 200 kW (higher powers upon request)
- Mains voltage 3~ 400 V, 50 Hz
- Ambient temperature 0 to + 40 °C max

Contents

1
Principles

1.1
Hydraulic Principles

1.1.1
Pump Principles

The task of a pump is to generate pressure and flow in a liquid. Various pump configurations have been developed to achieve this task. The most important designs are the positive-displacement pump and the centrifugal pump.

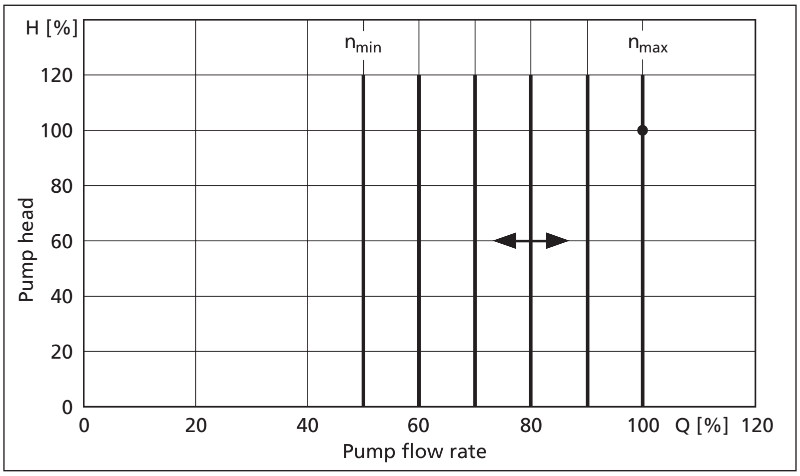


Fig. 1 Typical characteristic curves of a positive-displacement pump at various speeds

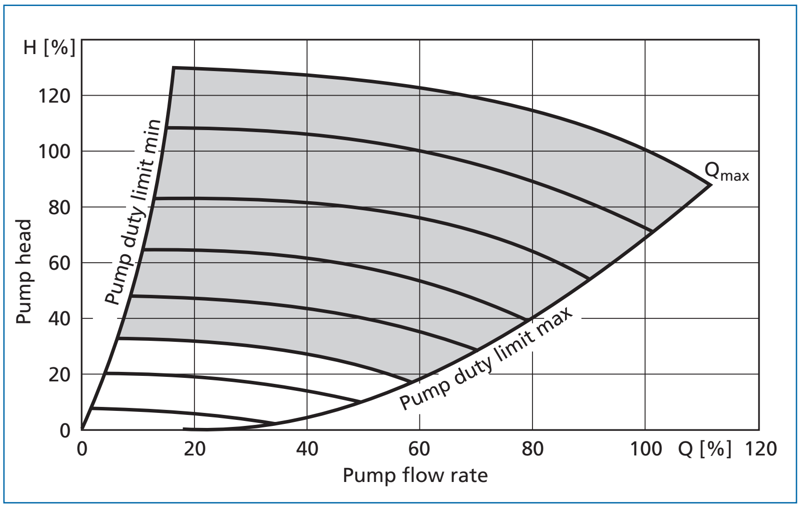


Fig. 2 Typical working range of a centrifugal pump with pump characteristic curves for different pump speeds

Positive-displacement pumps

These pumps are primarily used in cases where low flow rates are required in combination with a large pump head. Their working principle is based upon the periodic change in volume of cavities that are separated from the suction and discharge pipe by separating elements.

Typical examples are:

- Reciprocating piston pump
- Positive-displacement pump
- Diaphragm pump
- Gear pump
- Screw pump
- Vane pump
- Hose pump, etc.

Their main common features are:

The flow rate varies with the rotational or stroke speed. The head, on the other hand, is independent of this. Due to this behaviour, positive-displacement pumps must be protected against impermissibly high pressures. A change in the flow rate is only possible as a result of a change in the rotational or stroke speed, or due to additional devices (bypass). The pump characteristic curve shows the relationship between flow rate and head (pump pressure) at a constant speed.

If the speed changes there is a proportional change in the flow rate.

Centrifugal pumps:

Centrifugal pumps are used for most technical applications. This is due in particular to the following properties:

- Robust construction
- Simple design
- Cost-effective manufacture
- "Good natured" operating behaviour
- Good adjustability

The working principle of the centrifugal pump is based upon energy transfer by flow diversion as well as an additional centrifugal force effect in radial impellers. In contrast to positive-displacement pumps the maximum pump pressure is limited by the operating principle. Special devices to protect against overpressure are seldom necessary. Based upon the assumption that the drive speed is constant, different flow rates can simply be achieved by means of a throttling valve. The permissible working range is shown in the pump characteristic curve.

1.1.2
Flow Rate Adjustment

Flow Rate Adjustment by Throttling

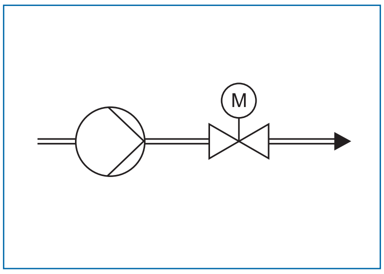


Fig. 3 Throttling configuration

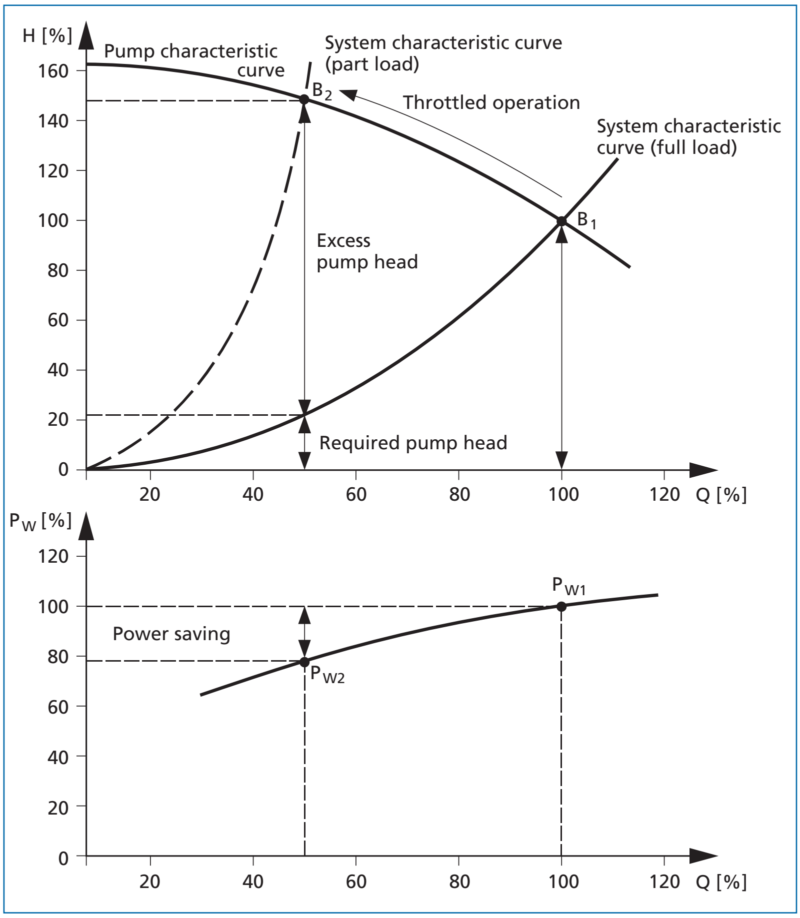


Fig. 4 Pump and power characteristic curves

The purpose of increasing the system resistances – the fitting of a restriction (throttling) – is to make the resulting system characteristic curve steeper. At a constant pump speed the operating point on the pump characteristic curve is moved to a lower flow rate. The pump thus generates a higher pressure (head) than is necessary for the system. The excess head thus created is broken down in the restricting fitting to create a pressure drop.

Evaluation

+ Lower control cost
+ Advantageous at mainly full load operation
+ Suitable for applications with short operating periods
+ Well suited for flat pump characteristic curves

– Pump pressure too high, particularly where the pump characteristic curve is steep
– Poor pump efficiency in part load operation
– Low power saving in part load operation
– Unfavourable control behaviour when the excess head is high
– Throttle valve necessary
– Mechanical load on the throttle valve
– Danger of flow noise at high levels of throttling (e.g. in thermostat valves).

Flow Rate Adjustment Using a Bypass

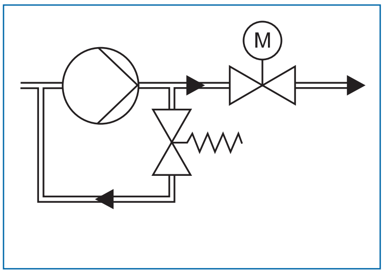


Fig. 5 Bypass configuration

The bypass line is arranged in parallel to the pump. The pump flow is thus divided into the useful flow, which flows into the system, and the bypass flow, which is directly or indirectly returned to the inlet pressure side of the pump (see Fig. 5). Changing the bypass flow rate or the bypass line characteristic curve by means of a control valve thus allows the useful flow to be varied. The pump itself runs at almost the same operating point, i.e. at the system's design point, in full load operation.

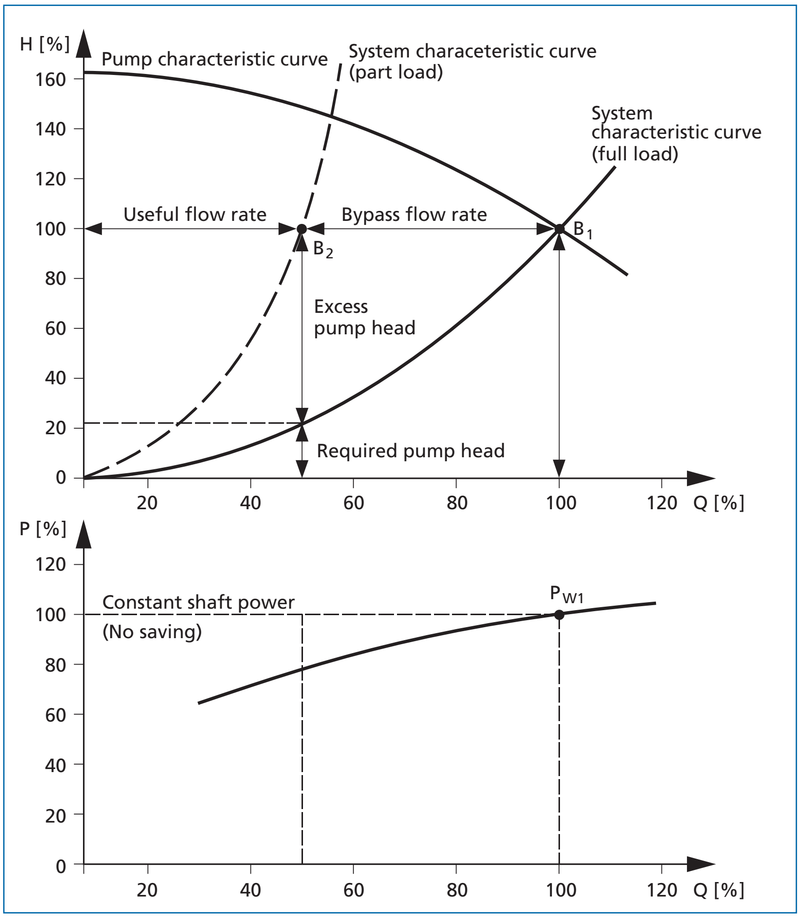


Fig. 6 Pump and power characteristic curves

Evaluation

+ No increase in head even in part load operation
+ In contrast to throttling the pump pressure remains constant when the flow is adjusted
+ Suitable in situations where low head is combined with high flow rates
+ Well suited if full load operation prevails

– Increased construction costs (bypass circuit)
– No reduction of the power consumption in part load operation
– In part load operation there is still excess head
– This method of flow rate adjustment is uneconomical in terms of energy used

Flow Rate Adjustment by Parallel Operation of Pumps

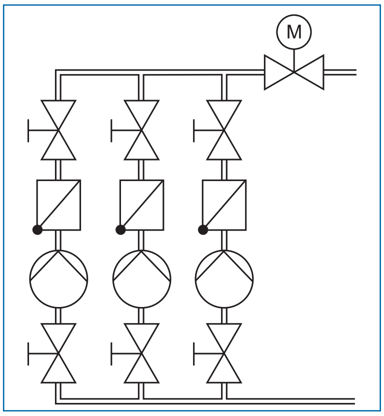


Fig. 7 Parallel pump connection

If pumps are connected in parallel as shown in Fig. 7 their partial flow rates are summed.

For the construction of the parallel operation characteristic curves, the partial flow rates of all participating pumps are summed at several different pressure levels (between zero and minimum head). The parallel characteristic curve is found by summing the flow rates at the same head. In practice it should be taken into account that as the flow rate increases the system resistances also rise and thus the actual operating point in parallel operation also lies at this higher pressure level. As a result, the increase in the flow rate is less than originally expected.

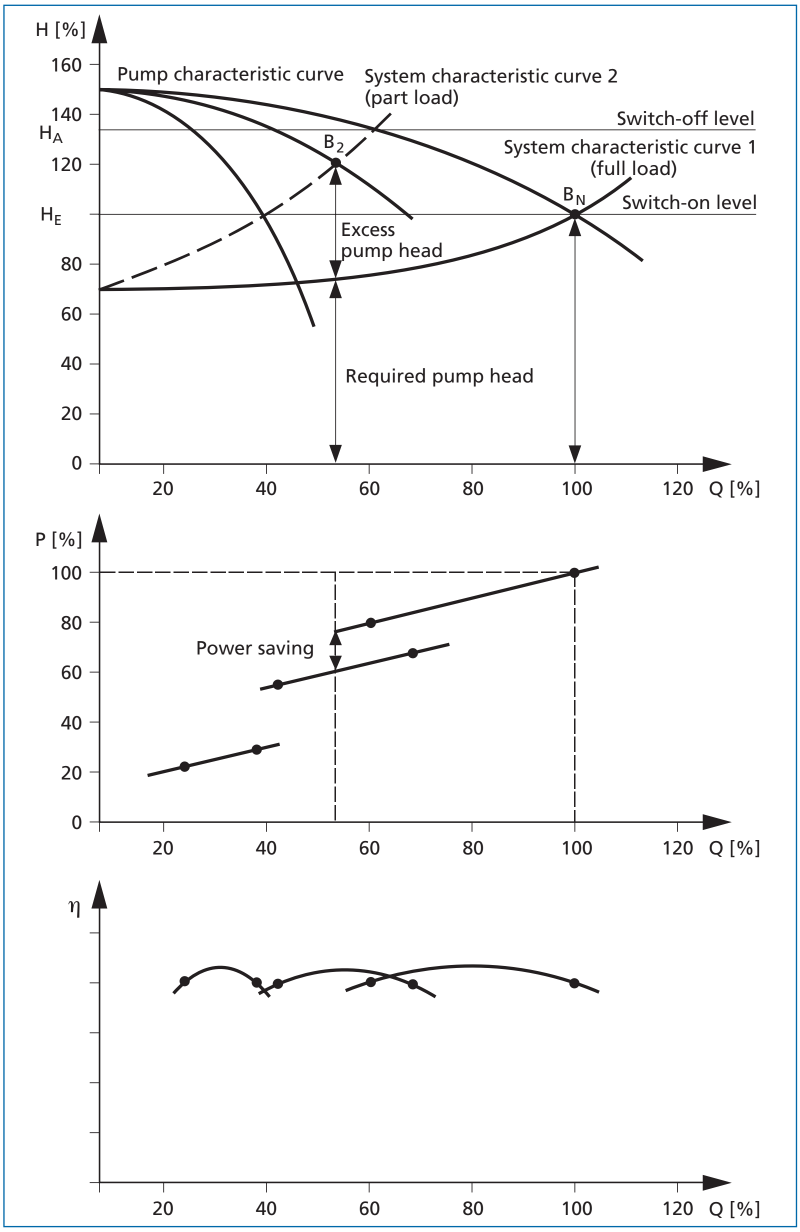


Fig. 8 Pump, power and efficiency characteristic curves for one, two and three pumps in parallel operation

Evaluation

+ Very well suited to flat system characteristic curves with a high static head component
+ Good adaptation to part loads
+ High system efficiency
+ Low control cost for pressure-dependent pump operation
+ High operating reliability due to several pumps (redundancy)

– Increased construction cost (piping, valves, pumps, space requirement)
– High switching frequency in unfavourable system designs
– In the event of flat pump/system characteristic curves pump operation is flow-dependent
– Problematic in the event of high inlet pressure fluctuations

Flow Rate Adjustment by Speed Adjustment

Relationships in the continuous speed adjustment of centrifugal pumps

Unlike the procedures for flow rate adjustment mentioned in the preceding sections, continuous speed adjustment permits a continuous modification of the pump output to the system requirements by changing the pump characteristic curve. If the flow rate increases linearly, the system resistance (piping characteristic curve) increases quadratically. The centrifugal pump behaves in a similar manner. In the event of linearly increasing flow rate and linearly increasing speed the resulting head also increases quadratically. As a result of these relationships even relatively small speed changes cover a wide working range. According to the similarity law the following relationships apply to centrifugal pumps (see Fig. 9):

Flow rate	$Q_2 = Q_1 \cdot \left(\frac{n_2}{n_1}\right)$
Discharge head	$H_2 = H_1 \cdot \left(\frac{n_2}{n_1}\right)^2$
Power input	$P_2 = P_1 \cdot \left(\frac{n_2}{n_1}\right)^3$

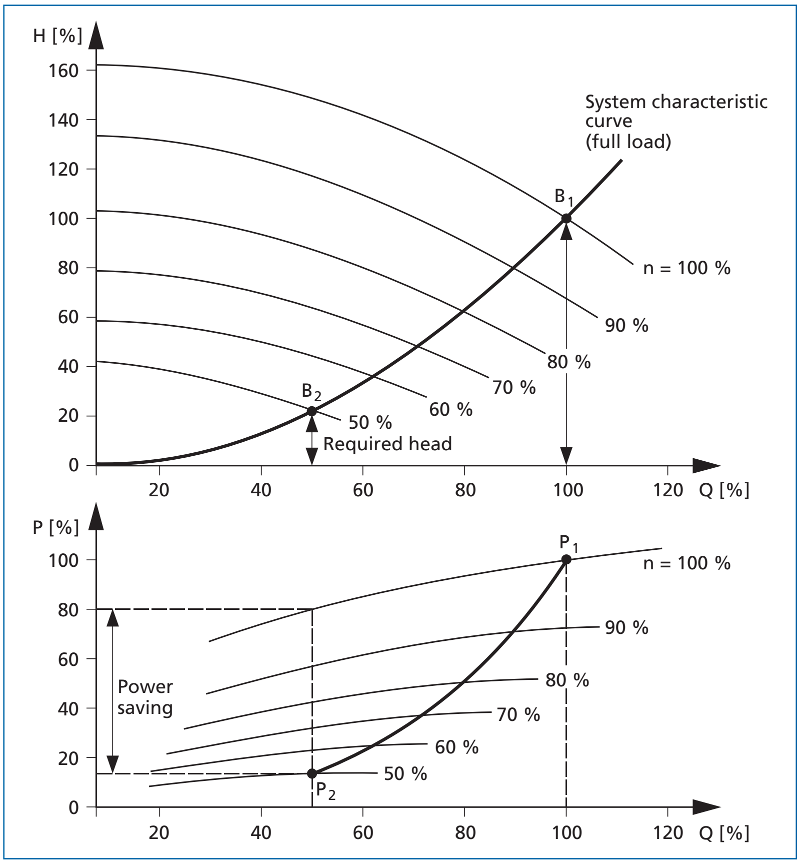


Fig. 9

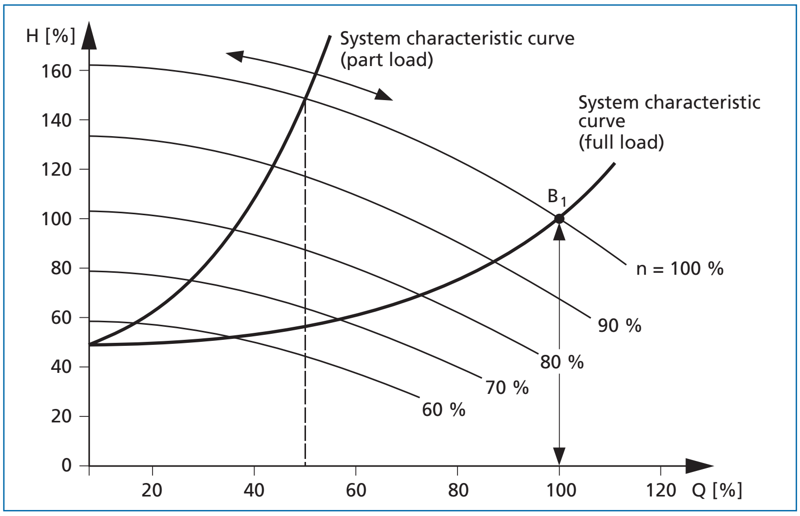


Fig. 10 Operation of a variable speed pump at different system characteristic curves

Real systems

In practice, it is common to find systems in which the consumption behaviour requires variable throttling or mixing processes.

The task of continuous pump speed adjustment is to cover the current system demand at the lowest possible speed (= cost).

Evaluation

+ Avoidance of excess pressure
+ Soft starting of the pumps via the frequency inverter
+ See also Chapter 4
+ Protection (wear reduction) of mechanical components
+ Reduction of hydraulic feedback effects
+ Power saving
+ Low grid load due to reduced starting currents
+ Reduction of life cycle costs
– Higher control costs

Flow Rate Adjustment by a Combination of Parallel Operation and Variable Speed Operation

The division of the flow into several pumps is used in all applications where demand fluctuates substantially and where the following requirements must be met:

- Minimization of power consumption
- Reduction of system costs
- Compliance with minimum pump flow rate

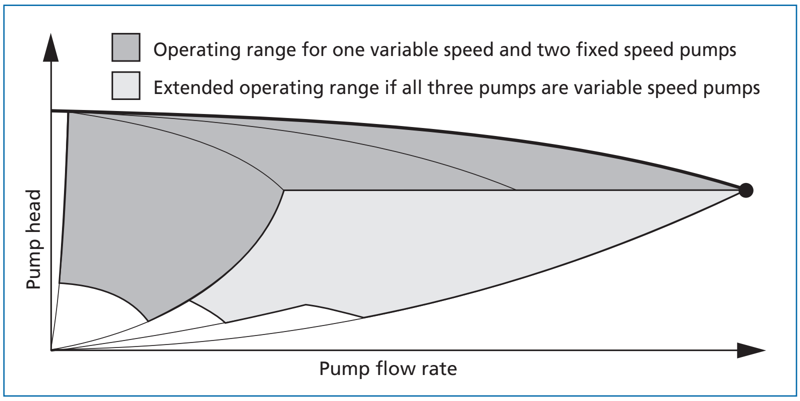


Fig. 11

A first approximate adjustment of the pump output to the system demand takes place by parallel operation.

The fine adjustment is achieved by infinitely variable speed adjustment of one or more centrifugal pumps.

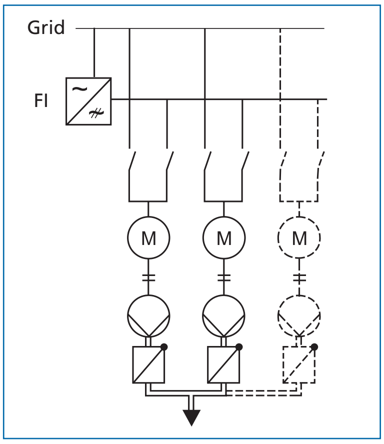


Fig. 12 One variable speed pump

Evaluation of one variable speed pump

+ Broad flow rate adjustment range (with limited head range)
+ High control quality
+ Redundancy on the pump side
+ Reduced switching frequency
+ Reduced mechanical load
+ Reduced hydraulic feedback effects
+ Low drive energy costs
+ Swapping of the variable speed pump possible

– Limited use in the event of inlet pressure fluctuations
– Limited working range in variable speed operation
– Medium purchase costs

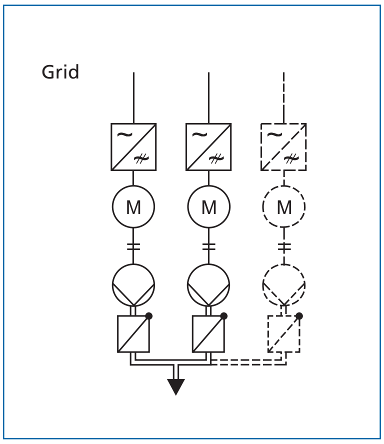


Fig. 13 Several variable speed pumps

Evaluation of several variable speed pumps

+ Increased flow rate and head adjustment ranges
+ Use with high inlet pressure fluctuations
+ Low energy use as a result of optimal inlet pressure utilization
+ Large variation possible in the set value range
+ Excellent control quality
+ Full redundancy (pumps and frequency inverters)
+ Greatly reduced switching frequency
+ Greatly reduced mechanical loading
+ Greatly reduced hydraulic feedback effects
+ Extremely low drive energy costs
+ Pump change possible without influencing the control quality

– High purchase costs

1.1.3 Characteristic Curve Conversion at Variable Pump Speed

If the pump and pumped fluid are the same, the performance data for a centrifugal pump in variable speed operation vary according to the following modelling / affinity laws:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2}$$

Equation 1

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2$$

Equation 2

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3$$

Equation 3

In what follows, the pump characteristic curves will be calculated for an example in which two pumps are operated in parallel (one pump continuously speed controlled, the second operated at a fixed speed).

For simplification, we make the assumption of a closed circuit without static counterpressure. Using the calculation methods represented the user can also solve cases with single pumps or even multi-pump systems. For a deeper understanding of the hydraulic interplay between pump characteristic curve and system characteristic curve, we recommend that you work through a few systems yourself, following the pattern given. For daily work IT programs conveniently support the calculation.

The aim of the following calculation processes is to create a pump performance chart which includes all important characteristic curves.

- Piping characteristic curve (system characteristic curve)
- Controlled-operation curve
- Pump characteristic curve (nominal speed)
- Affinity parabolas
- Pump characteristic curves (for reduced speeds)
- Pump characteristic curves for parallel operation
- Power characteristic curves, (fixed speed / variable speed) for single pump operation and parallel operation

These results form the basis of any economic calculation to be performed.

For the further calculation process it is helpful to derive an equation that creates a relationship between head and flow rate. To this end, equation 1 is squared and inserted into equation 2 (equation 4).

$$\frac{H_1}{H_2} = \left(\frac{Q_1}{Q_2}\right)^2 = \left(\frac{n_1}{n_2}\right)^2$$

Equation 4

Rearranging once again gives equation 5.

$$H_1 = H_2 \cdot \left(\frac{Q_1}{Q_2}\right)^2$$

Equation 5

This equation allows us to calculate a second order parabola from the origin (Q = 0, H = 0) through a point B_2 (H_2, Q_2) in the H/Q diagram. The values of H_2 and Q_2 are known, since the parabola is to cut through this point.

H_1 and Q_1 are unknown and will therefore be denoted as H_x and Q_x in what follows.

The flow rate Q_x will, depending upon the necessary accuracy, be assumed for several points on the parabola and H_x then calculated according to the derived formula.

The value pairs Q_x and H_x are shown in table form in what follows for the sake of a better overview.

Key:

B:	Operating point
H:	Head
Q:	Flow rate
n:	Pump speed
P:	Power input at the pump shaft
x:	Sought quantity

Indices:

N:	Nominal
0:	At zero flow
1; 2:	Pump 1; Pump 1 + 2 in parallel
...’:	In fixed speed operation
W:	Leading value
Z:	Intermediate points

Calculation of the Piping Parabola using Equation 5

The piping characteristic curve in a closed system runs from the origin to the operating point B_N (full load).

$$H_x = H_N \cdot (Q_x / Q_N)^2$$
$$H_x = 100\ \% \cdot (Q_x / 100\ \%)^2$$

Given Q_x	Sought H_x
25	6
50	25
75	56
110	121

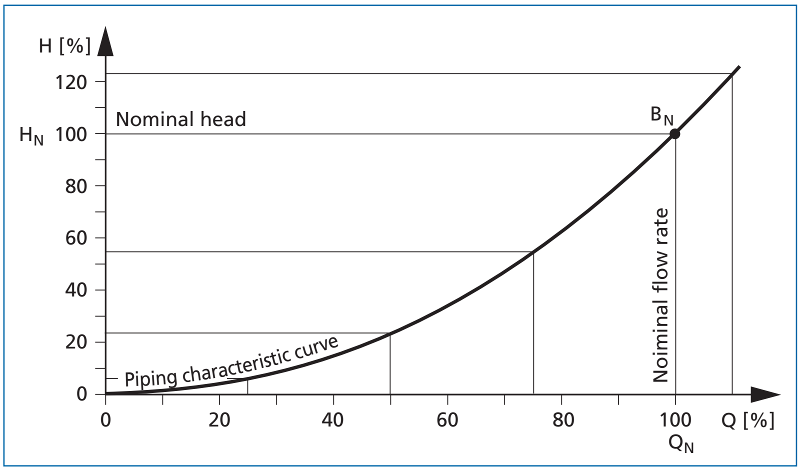


Fig. 14

Note:
The piping / system characteristic curve for open systems with static counterpressure is explained in Chapter 1.2.5.

Calculation of the Controlled-operation Parabola

The origin of the parabola is shifted to the level of the set value by means of a small expansion of the equation (see p. 27, Fig. 55 and p. 50, Fig. 77)

$$H_x = (H_N - H_W) \cdot (Q_x / Q_N)^2 + H_W$$
$$H_x = 35\ \% \cdot (Q_x / 100\ \%)^2 + 65\ \%$$

Given Q_x	Sought H_x
25	67
50	74
75	85

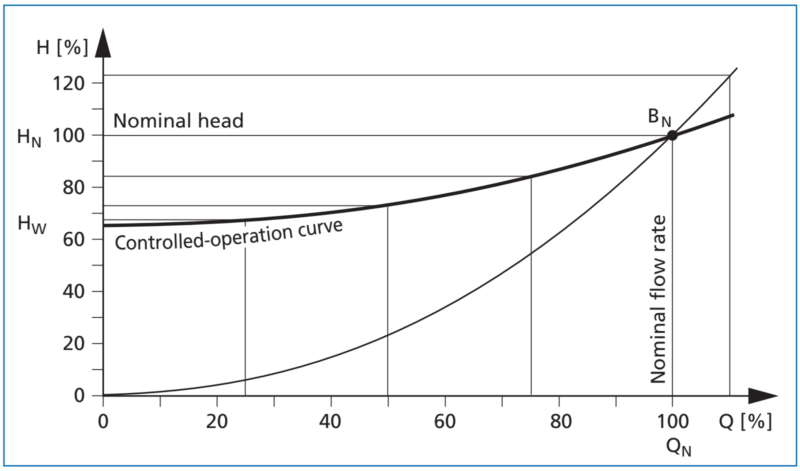


Fig. 15

The controlled-operation characteristic curve is a theoretical curve along which the operating point should move.

It ensures that from the minimum to the nominal flow rate there is always sufficient pump head available to cover the piping pressure losses and the useful pressure at the consumer installation.

The value H_W is dependent upon the following influencing factors:

- Operating behaviour of the consumer installation
- Similar load behaviour over time or time-independent load behaviour
- System dimensioning

Pump Selection

A pump is selected that achieves the nominal head (B'_2) at half the nominal flow rate.

In addition, the pump characteristic curve must at least intersect the controlled-operation curve ($B_{1,\,max}$) (see also Chapter 1.1.1).

In systems with two pumps (without a stand-by pump) in the event of the failure of a pump at least the system characteristic curve must be intersected ($B_{1,\,fault}$), since otherwise the remaining pump will be overloaded

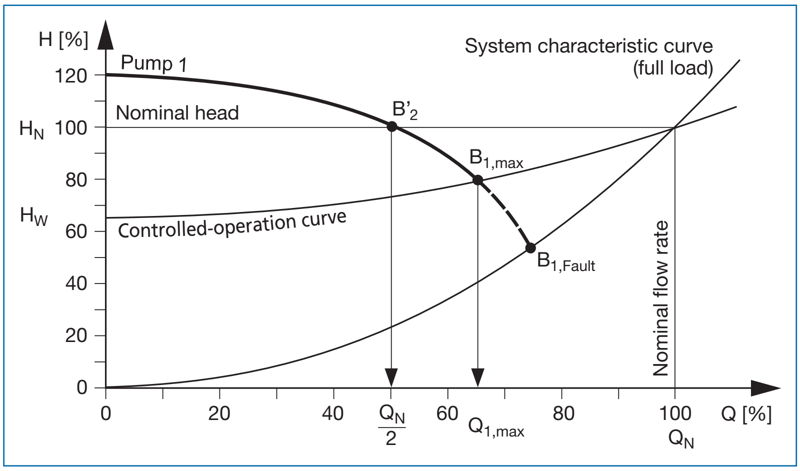


Fig. 16

Calculation of the Affinity Parabola by: B'_2 (Q'_{B2}, H'_{B2})

According to the laws of affinity the operating point B'_2 moves along the affinity parabola when pump speed is reduced. The path of the affinity parabola is found using the equation below. It yields the working point B_2 on the controlled-operation curve.

$$H_x = H_N \cdot (Q_x / Q'_{B2})^2$$
$$H_x = 100\,\% \cdot (Q_x / 50\,\%)^2$$

Given Q_x	Sought H_x
15	9
25	25
35	56

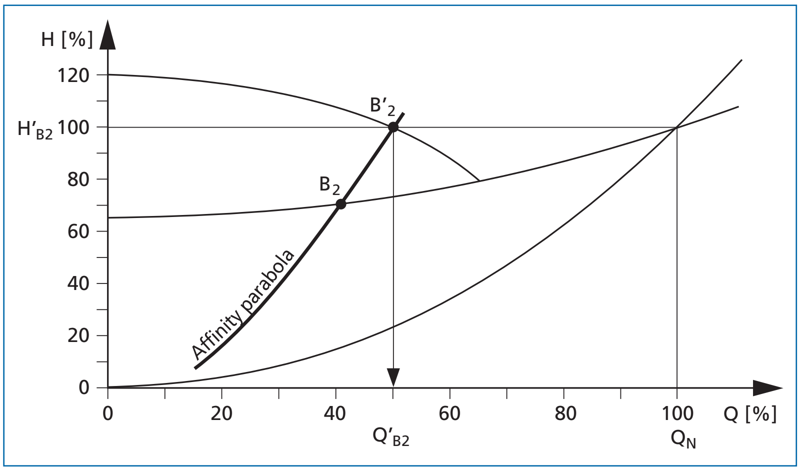


Fig. 17

Calculation of the Affinity Parabola by: B'_1 (Q'_{B1}, H'_{B1})

Using the same calculation process as before a further point (B_1) on the controlled-operation curve is found.

In many cases it is worthwhile selecting the point B_1 at half the pump flow rate.

$$H_x = H'_{B1} \cdot (Q_x / Q'_{B1})^2$$
$$H_x = 115\ \% \cdot (Q_x / 25\ \%)^2$$

Given Q_x	Sought H_x
10	18,4
15	41,4
20	73.6
25	115.0

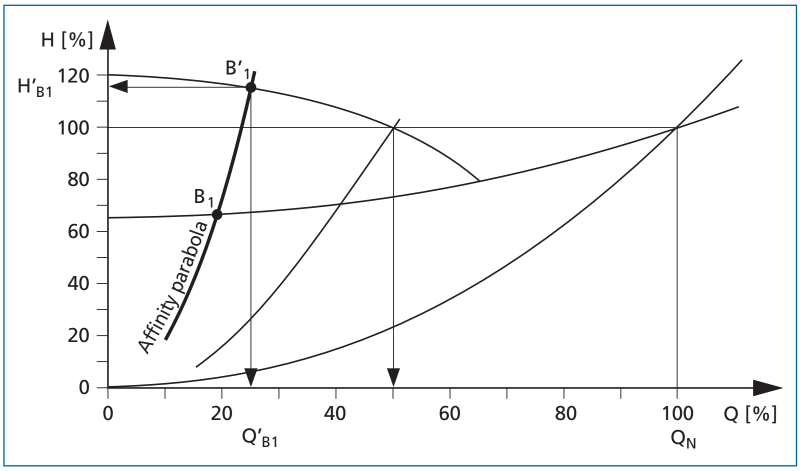


Fig. 18

Pump Characteristic through B_2 at Pump Speed n_2

The precise values can also be determined by calculation. For practical use the read-off values are perfectly adequate.

We read off:

Q_{B2} = 42 %; H_{B2} = 71 %

Using the equations given below we first calculate the reduced speed for the operating point B_2 from the ratio of heads.

Speed at B_2:

(Q_{B2} = 42 %, H_{B2} = 71%)

$$n_2 = n_N \cdot \sqrt{\frac{H_{B2}}{H'_{B2}}}$$
$$n_2 = 100 \cdot \sqrt{\frac{71\ \%}{100\ \%}} = 84\ \%$$

In the second step the head at zero flow point $H_{0.2}$ is calculated for this speed n_2. This

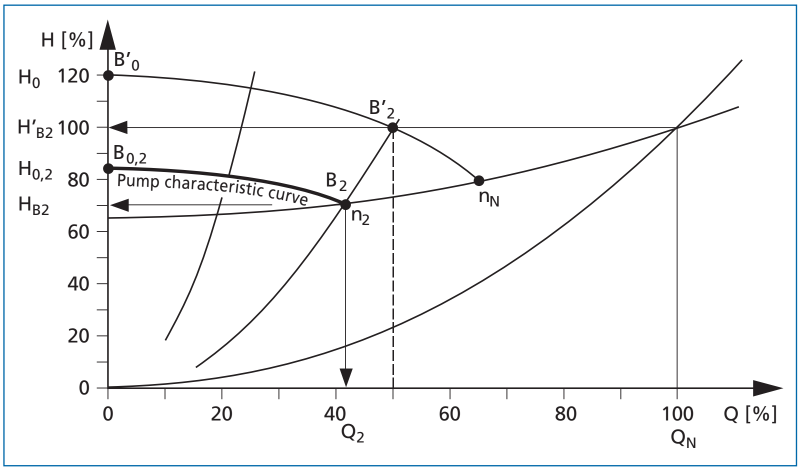


Fig. 19

allows us to draw the pump characteristic curve for n_2 with sufficient accuracy.

Head at Q = 0 and n = n_2

$$H_{0.2} = H_0 \cdot (n_2 / n_N)^2$$
$$H_{0.2} = 120\ \% \cdot (84\ \% / 100\ \%)^2 = 85\ \%$$

Pump Characteristic Curve through B_1 at Speed n_1

The pump characteristic curve through the operating point B_1 is calculated using the same calculation process as before.

Speed at B_1:
(Q_1 = 19 %, H_1 = 66 %)

$$n_1 = n_N \cdot \sqrt{\frac{H_{B1}}{H'_{B1}}}$$

$$n_1 = 100 \cdot \sqrt{\frac{65\ \%}{115\ \%}} = 76\ \%$$

Head at Q = 0 and n = n_1

$$H_{0.1} = H_0 \cdot (n_1 / n_N)^2$$

$$H_{0.1} = 120\ \% \cdot (76\ \% / 100\ \%)^2 = 69\ \%$$

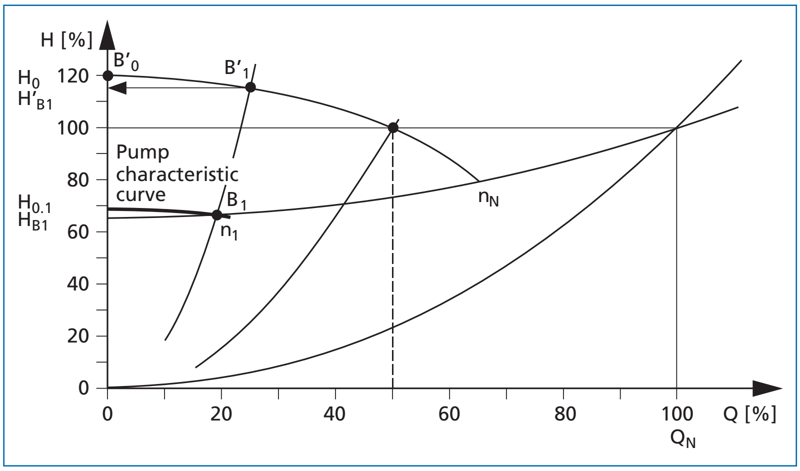


Fig. 20

Addition of the Pump Characteristic Curves

The parallel operation characteristic curve is found by adding the flow rates of the two individual characteristic curves:

Pump 1, fixed speed,
with nominal speed n_N

Pump 2, variable speed,
with speed n_2

Starting from shut-off head H_0 up to head $H_{0.2}$ the flow rate is generated by pump 1 alone. Pump 2 cuts in at the point B'_4 as counterpressure decreases. The summed characteristic curve of the two pumps intersects with the controlled-operation curve at B_4 and head H_4.

At this pressure level pump 1 provides the flow from Q_0 to Z'_4 and pump 2 provides the flow from Z'_4 to B_4.

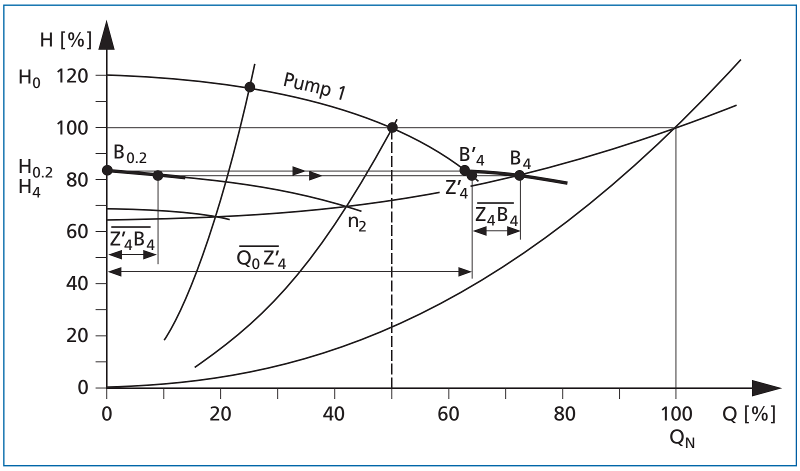


Fig. 21

Determination of Auxiliary Points and Intermediate Characteristic Curves

a) Operating point B_3 with auxiliary point Z_3

Since the operating points B_N and B'_4 are quite a long way apart an additional operating point B_3 is placed in between. The point Q_{B3} = 85 % was selected with the associated head H_{Z3}. At operating point B_3 the pump delivers a flow at reduced speed, which is represented by the distance between the points Z_3 and B_3.

For the construction of a pump characteristic curve for reduced speed this distance is moved left to the origin at head H_{Z3}. The end point is Z_3.

We read off:
Distance $\overline{Z_3B_3}$ = 26 %.

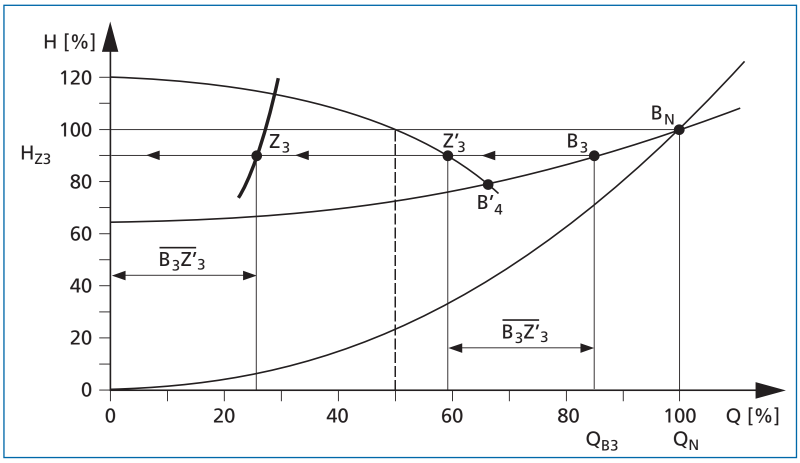


Fig. 22

b) Calculation of the affinity parabola through Z_3 (Q_{Z3}, H_{Z3})

For the construction of the intermediate characteristic curve it is necessary to convert the point Z_3 to the nominal speed B_3. To this end an affinity parabola is placed through the point Z_3.

We read off: H_{Z3} = 90 %.

$$H_x = H'_{Z3} \cdot (Q_x / Q_{Z3})^2$$
$$H_x = 90\ \% \cdot (Q_x / 26\ \%)^2$$

Given Q_x	Sought H_x
20	53
30	120

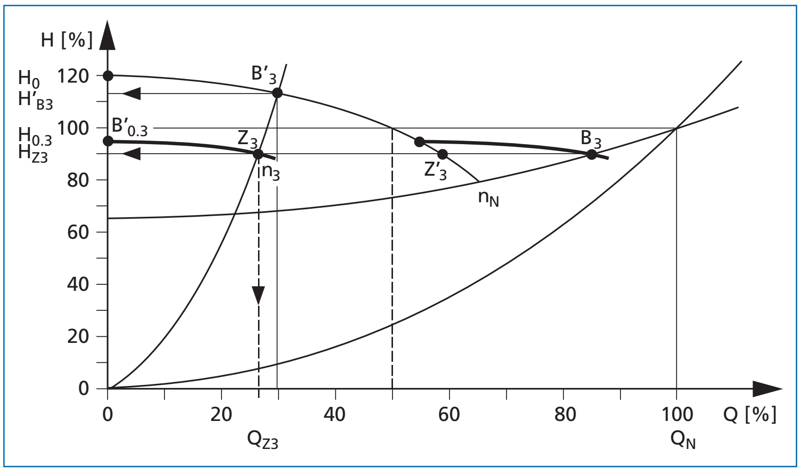


Fig. 23

c) Pump characteristic curve through B_3 (Z_3) at speed n_3

Determination of the speed at n_3

H'_{B3} = 113 % (read off)

(Q_{Z3} = 26 %, H_{Z3} = 90 %)

$$n_3 = n_N \cdot \sqrt{\frac{H_{Z3}}{H'_{B3}}}$$
$$n_3 = 100 \cdot \sqrt{\frac{90\ \%}{113\ \%}} = 89\ \%$$

Determination of the head at Q = 0 and n = n_3

n_3 (calculated)

H_0 (read off)

$$H_{0.3} = H_0 \cdot \left(\frac{n_3}{n_N}\right)^2$$
$$H_{0.3} = 120\ \% \cdot \left(\frac{89\ \%}{100\ \%}\right)^2 = 95\ \%$$

Addition of the Characteristic Curves of Equally Sized Pumps 1 and 2 at Nominal Speed

At a head of 100 %, for example, the distance to the intersection with the characteristic curve of pump 1 is measured and the same distance marked off to the right of the intersection.

Using this procedure, depending upon the accuracy requirement, further points for the summed characteristic curve of the two equally sized pumps 1 and 2 are found.

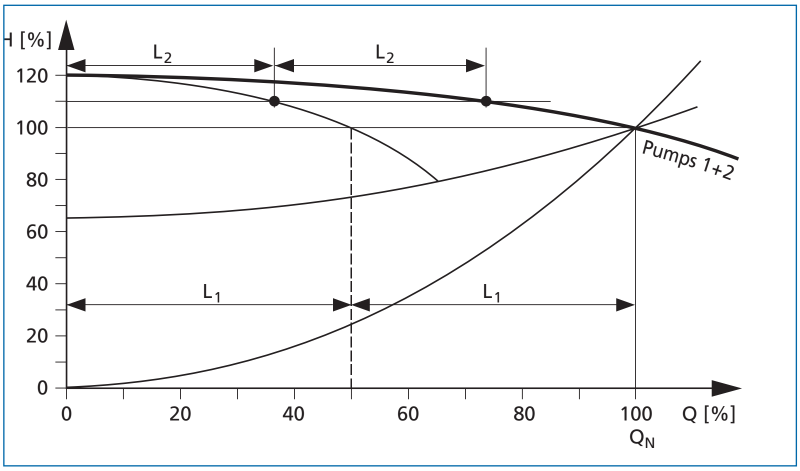


Fig. 24

Input Power of Two Pumps Operated in Parallel at Nominal Speed

This requires that the input power of a pump is known. The total input power in parallel operation is sought. At point B_N both pumps have an input power of P'_2. This means that both pumps consume the double power P'_2 x 2. In this manner the points P'_3 x 2 and P'_1 x 2 were also found.

P_w = pump input power (shaft power)

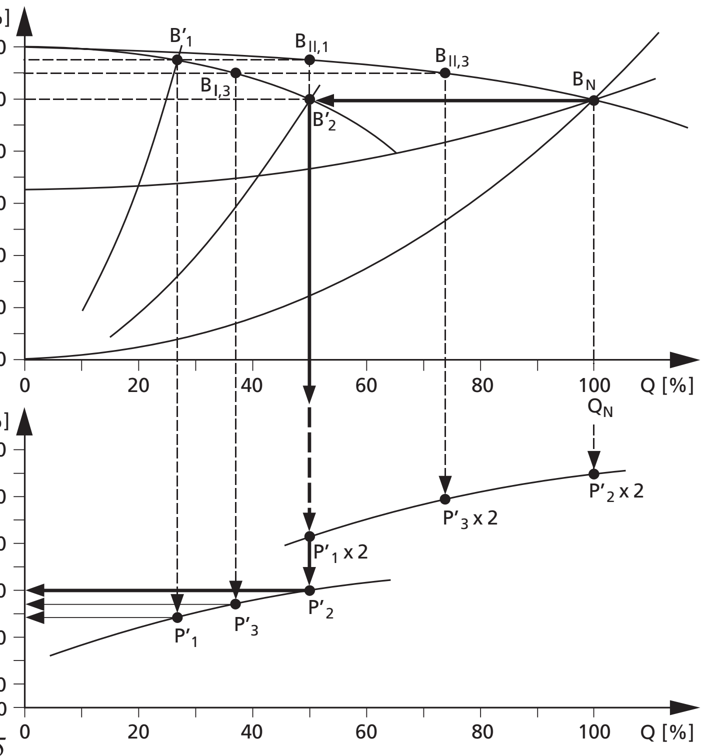


Fig. 25

Input power of pump 1 in variable speed operation

The reduced speeds have been determined by the previous stages. Since the input power is known for fixed speed operation, the input power in question in variable speed operation can be calculated.

$$P_1 = P'_1 \cdot \left(\frac{n_1}{n_N}\right)^3$$

$$P_1 = 74\ \% \cdot \left(\frac{76\ \%}{100\ \%}\right)^3 = 32.5\ \%$$

$$P_2 = P'_2 \cdot \left(\frac{n_2}{n_N}\right)^3$$

$$P_2 = 100\ \% \cdot \left(\frac{84\ \%}{100\ \%}\right)^3 = 59.3\ \%$$

$P_{I,max}$ = Input power as for fixed speed operation, since the speed is 100 % = n_N

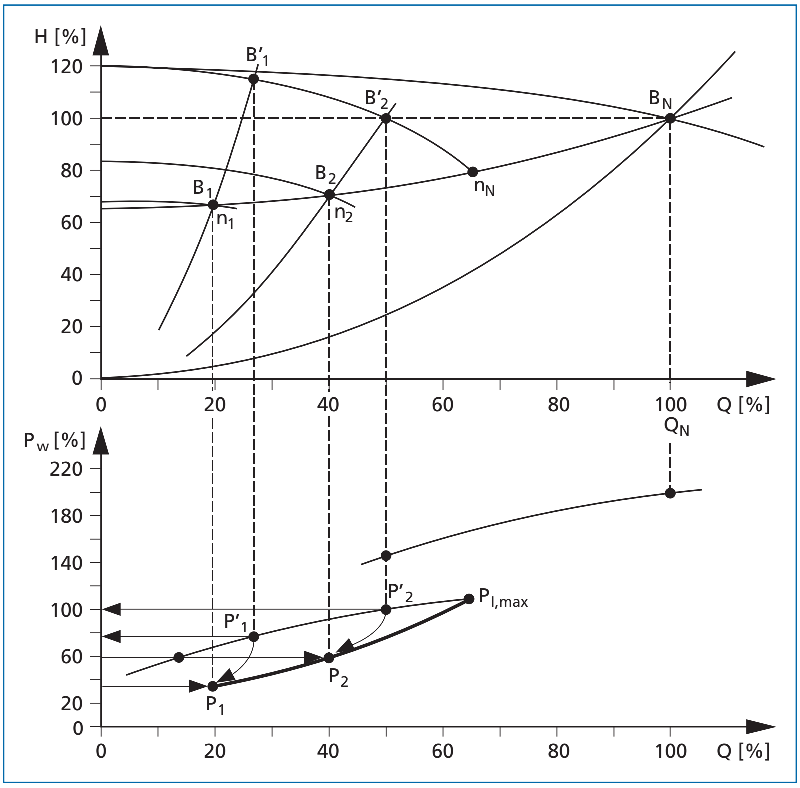


Fig. 26

Pump input power in parallel operation

(Pump 1 at n_N,
Pump 2 at n = variable)

Starting from point B_3, go horizontally left to Z'_3, and from this point vertically down to P'_3. P'_3 is the input power of the fixed speed pump.

$P_3 = P'_3 + P_{3,\,n_3}$

To determine the proportional power of the variable speed pump $P_{3,\,n_3}$ we use equation 3 (page 8). We thus find:

$$P_{3,n_3} = P'_{3,n_N} \cdot \left(\frac{n_3}{n_N}\right)^3$$

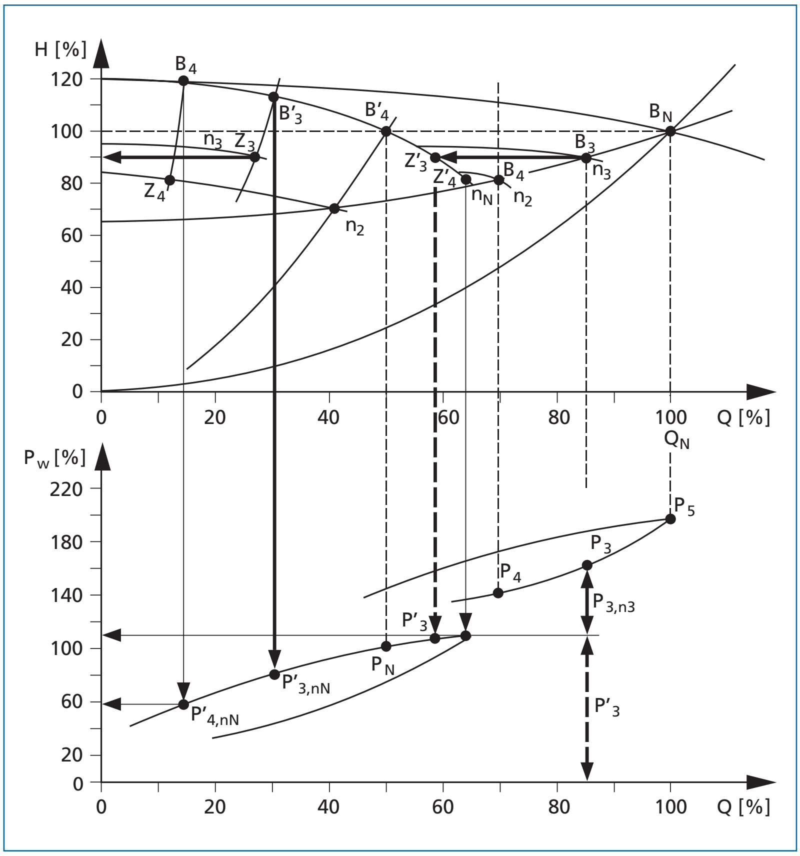


Fig. 27

The further points are determined in the same way

$$P_3 = P'_3 + P'_{3,n_N} \cdot \left(\frac{n_3}{n_N}\right)^3$$

$$P_3 = 108\ \% + 80\ \% \cdot \left(\frac{89\ \%}{100\ \%}\right)^3$$

$$P_3 = 164.4\ \%$$

$$P_4 = P'_4 + P'_{4,n_2}$$

$$P_4 = P'_4 + P'_{4,n_N} \cdot \left(\frac{n_4}{n_N}\right)^3$$

$$P_4 = 112\ \% + 52\ \% \cdot \left(\frac{84\ \%}{100\ \%}\right)^3$$

$$P_4 = 143\ \%$$

$$P_5 = 2 \cdot P_N = 2 \cdot 100\ \% = 200\ \%$$

Minimum Set Value in Parallel Operation of Available Pumps

At a given maximum pump flow rate (Caution: motor power reserve) the minimum target value to be set can be calculated as follows:

$$H_{W,min} = H_N - \left(\frac{H_N - H_{I,max}}{Q_N^2 - Q_{I,max}^2}\right) \cdot Q_N^2$$

$$H_{W,min} = 100\% - \left(\frac{100\% - 80\%}{100\%^2 - 65\%^2}\right) \cdot 100\%^2$$

$$H_{W,min} = 65\ \%$$

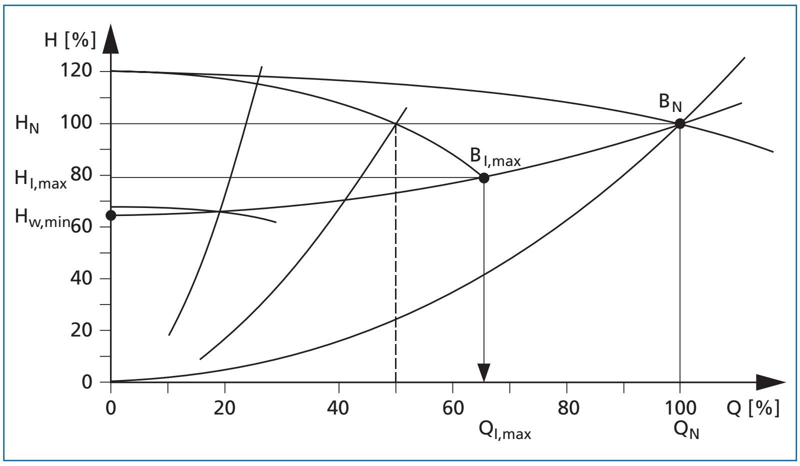


Fig. 28

Notes: Input power in the event of a speed change
If the speed is changed the points of a throttled-operation curve move along second order parabolas to the other throttled-operation curve. If the speed is reduced by less than 20 % of nominal speed the efficiencies remain almost constant. In the event of greater deviations the efficiency worsens slightly. Since the power requirement of the pump reduces by a power of 3 as the speed falls, the slight worsening of efficiency is not important. In the worked example no efficiency correction was made.

1.1.4 Economy Calculation for Infinitely Variable Speed Adjustment Systems with Frequency Inverter

How can the benefits of the pump control systems be demonstrated? To provide evidence it is necessary to know the influencing factors and their importance. For the economy of a pump system in relation to the pump output these are:

1. **The design of the system**
2. **The load distribution over time of the system**
3. **The pump**
4. **The pump power consumption from the electrical grid**

The following shows in more detail how these factors act.

Influences Due to the Design of the System

The operating point of a centrifugal pump is always the point of intersection between the system characteristic curve and the pump characteristic curve. All control methods thus change either the pump or the system characteristic curve.

The system characteristic curve denotes the pressure requirement of the system depending upon the flow rate. It always contains dynamic components that increase quadratically with the flow rate due to the flow resistances – for example in circulatory systems (heating).

However, it may also incorporate additional static components, such as differences in geodetic head or pressure differences caused by other factors – for example in transport systems (pressure boosting). In circulatory systems the system characteristic curve has no static components and thus begins at the origin (H = 0). In practice, to prevent consumer installations being undersupplied, the necessary pressure graph lies above the system characteristic curve. Its precise path is dependent upon the system in question.

The controlled-operation curve, along which the operating point should move, must consequently lie on or above the necessary pressure line.

Influences as a Result of the Loading of the System over Time

The flow rate Q of a centrifugal pump system can, in the most extreme case, fluctuate between a maximum value and zero. If we order the required flow rate over a year according to size we obtain the ordered annual load duration curve. Its precise path is dependent upon the system in question and can differ from one year to the next.

The Figure opposite shows two possible graphs. The longer the operating period and the smaller the area below the curve, the greater is the potential for possible savings.

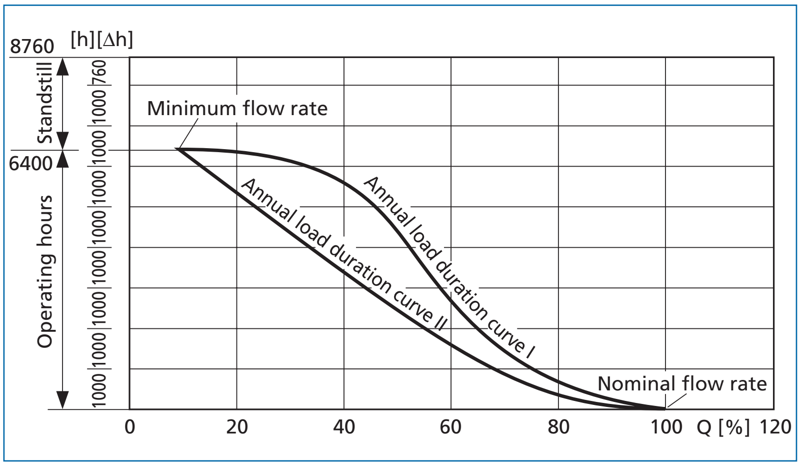


Fig. 29
Load profile (example): The pump is designed for 100 % flow rate. This output is seldom required in the year. Most of the time a lower flow rate is required. To save pump drive power the control system automatically matches the pump speed to the momentary system demand.

Influences of the Pump

The pump can influence the extent of possible savings realized by pump control in different ways: by the path of its characteristic curve, by the different motor sizes required and by the design of the pump. The graph of the pump input power depends upon the gradient of the head and the graph of pump efficiency. In general: The steeper the pump characteristic curve, the flatter the power characteristic curve.

The motor size of a pump unit has an influence, since experience tells us that the ratio of investment to motor size (€/kW) falls as the power increases.

In multi-pump systems (as in our example with 2 operating pumps) the economy calculation is performed according to the same way as described in the following sections.

The Pump Power Consumption from the Electric Grid

Chapter 1.1.3 only addressed the different pump input power requirements of the pumps (shaft power). However, if we want to precisely determine the electric drive power saved, the following relationships are also important:

Electric power consumption, fixed speed operation ($P_{E,\,u}$)

The power consumption in fixed speed operation is increased in relation to the pump shaft power ($P_{W,\,u}$) by the motor losses.

Electric power consumption, variable speed operation ($P_{E,\,g}$)

The power consumption in variable speed operation is determined by the shaft power $P_{W,\,g}$ plus the losses of the frequency inverter plus the motor losses (the motor losses may increase slightly depending upon the frequency inverter type).

The additional losses as a result of variable speed operation are negligible, since a power saving is achieved as soon as the flow rate falls below approx. 95 % compared to fixed speed operation (see Fig. 30).

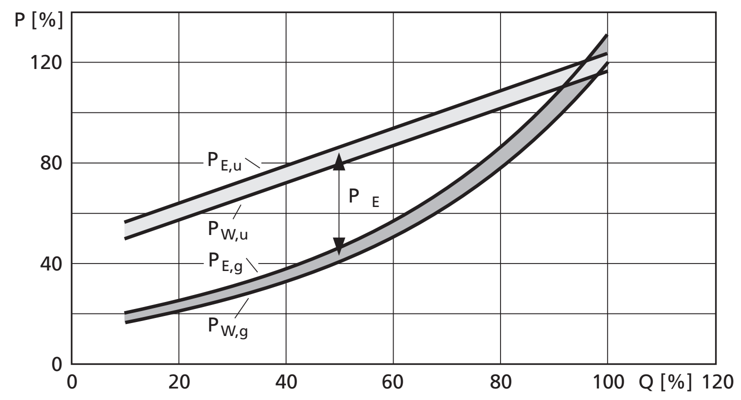


Fig. 30
Saved electric power
The shaded areas in the Figure show that the absolute electrical power losses in variable speed and fixed speed operation are almost identical. The higher losses of infinitely variable pump control in the full load range are compensated in part load operation.

For practical applications it is not necessary to determine the power consumption in detail. It is fully adequate to base calculations upon the pump input power (shaft power) in question. This is because, as shown in Fig. 30, the absolute electrical power losses in variable speed and fixed speed operation are almost identical.

Key:

P_W	= Pump input power (shaft power)
P_E	= Electric power consumption
u	= Fixed speed
g	= Variable speed
ΔP_E	= Saved electric power

A Comparison of Three Systems With and Without Speed Control

On the following pages we will compare systems with and without speed control:

- **In the H/Q diagram**
- **In the pump input power curve**
- **In the savings diagram**

The systems shown are closed circulation systems. The considerations and predictions can easily be applied to open transport systems, such as water supply systems or waste water systems, for example.

1) Throttling configuration with/without pump speed control

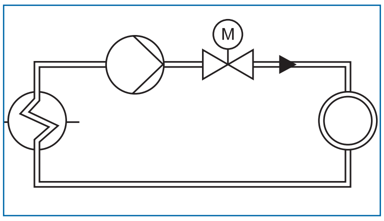


Fig. 31

Diagram: H/Q curve

The nominal flow rate, the nominal head and the nominal speed are each marked at 100%. The pump characteristic curve is drawn for several speeds in increments of 10 % from the nominal speed down. The system characteristic curve begins at the origin of the H/Q diagram, since it is a closed system, and its path is parabolic. The gradient of the system parabola is dependent upon the losses in the pipe network and thus also upon the throttling processes of the consumer installation. The fluctuation of the system characteristic curve permitted by the pump is limited by the minimum and maximum flow rate.

In practice the required pressure curve lies above the system characteristic curve. To prevent undersupply at any consumer installation, the pump pressure must always lie above this curve.

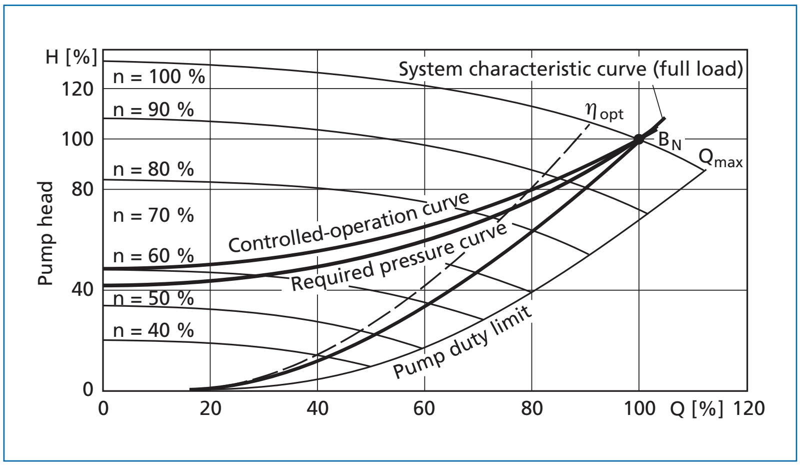


Fig. 32

However, for hydraulic and energy reasons the pump pressure should lie very close to this boundary. This means that the controlled-operation curve, along which the operating point (intersection of the system characteristic curve with the pump characteristic curve at the speed in question) moves, should lie as little as possible above the required pressure curve.

Diagram: Pump input power

As for the H/Q diagram, at nominal flow rate and nominal speed the pump input power is marked at 100 %. Like the pump characteristic curves, the input powers are also drawn at speed increments of 10 %.

As the operating point moves along the controlled-operation curve away from the design point to a lower flow rate, the associated shaft power of the pump can easily be determined. The intersection of the controlled-operation curve with the pump characteristic curve in question in the H/Q diagram is extended downwards until the power curve that corresponds with the speed is intersected in the input power diagram. The same procedure is followed for all intersection points.

The intersection points can then be joined together in the pump input power diagram, giving the shaft power requirements for variable speed adjustment. The shaft power saved by the speed adjustment lies between this curve and the input power in throttled operation and at constant speed.

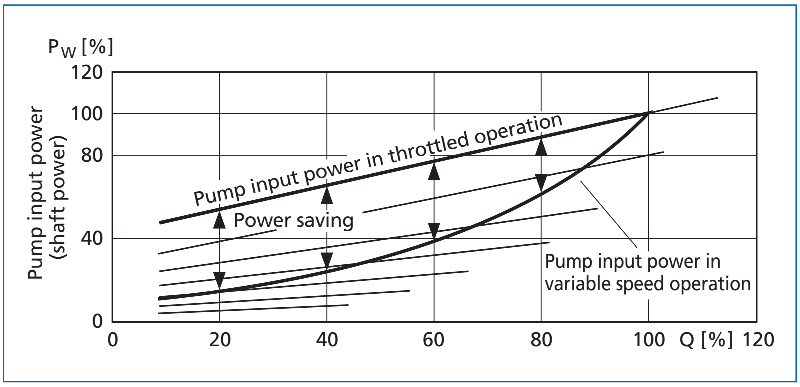


Fig. 33

Diagram: Saving

The saving found from the pump input power diagram is now transferred. The motor efficiencies in fixed and variable speed operation are already taken into account in this diagram, as are the frequency inverter efficiencies in variable speed operation. At nominal flow rate the saving is, of course, equal to zero or even negative, but at a reduced flow rate this rises considerably.

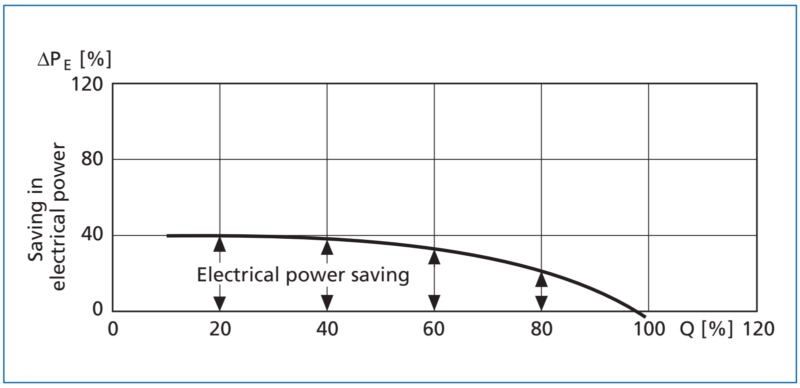


Fig. 34

2) Throttling configuration with overflow valve and with/without pump speed control

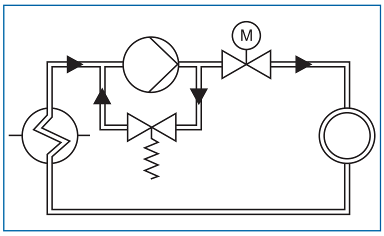


Fig. 35

Diagram: H/Q curve

The nominal flow rate, the nominal head and the nominal speed are each marked at 100 %. The pump characteristic curve is drawn for several speeds in increments of 10 % down from the nominal speed. The system characteristic curve begins at the origin of the H/Q diagram since this is a closed system. Its path is parabolic and should pass through the design point (100 %) for fully opened consumer installations. If the flow through the consumer installations is restricted, the overflow valve opens and allows the flow rate that is not required to be discharged. This means that the pump almost always works at almost full power. Without speed adjustment the possible pressure rise on the pump characteristic curve is limited by the overflow valve – with the great disadvantage that there is an almost continuous wastage of drive energy.

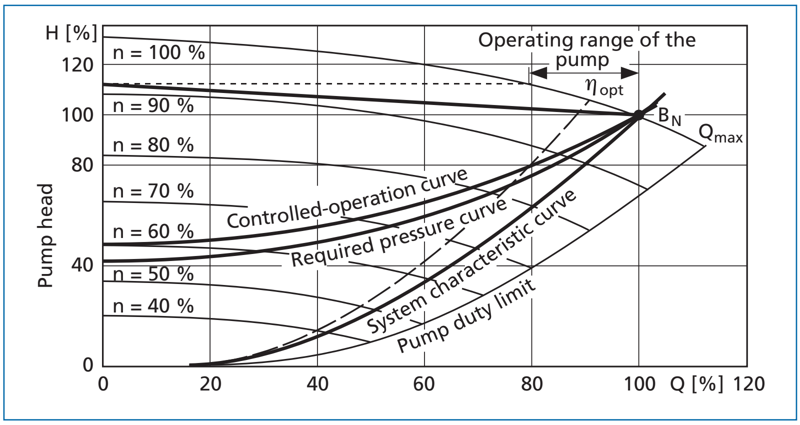


Fig. 36

Diagram: Pump input power

Here too, the pump input power is set equal to 100 % for the design point. The relatively narrow working range of the pump determined by the overflow valve leads to an almost constant pump input power requirement on fixed speed pumps. For a variable speed pump the bypass can remain closed, only the minimum flow rate of the pump must be guaranteed.

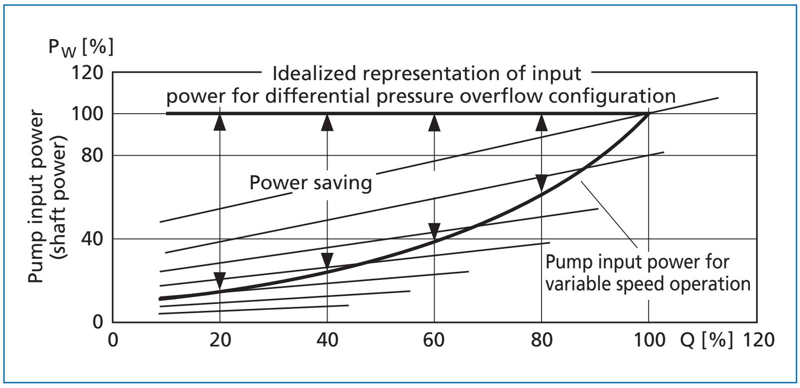


Fig. 37

The pump input power required in variable speed operation is determined in the same way as for pure throttling. This means that lines are drawn down from the intersections of the controlled-operation curves with the pump characteristic curves in the H/Q diagram until they intersect with the associated power curve (at the same speed) in the power diagram. By connecting these points we then obtain the shaft power requirement at the modified pump speed. The power saving is the difference between the horizontal characteristic of the fixed speed input power requirement and the curve of the shaft power required in variable speed operation.

Diagram: Saving

This power saving can again be shown in its own diagram. This clearly shows that the power saving potential resulting from variable speed operation in a system with an overflow valve is significantly greater than is the case for pure throttling.

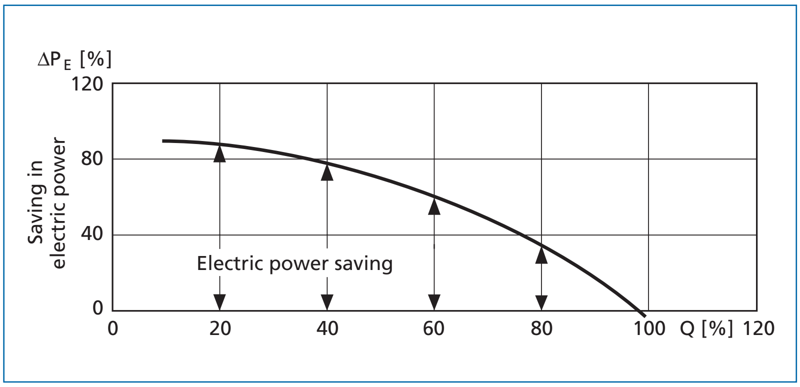


Fig. 38

3) Bypass configuration with/without pump speed control

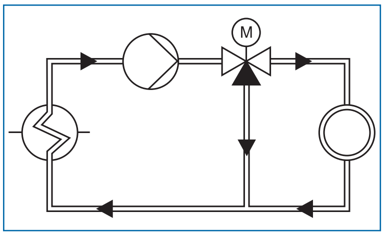


Fig. 39

Diagram: H/Q curve

The nominal flow rate, the nominal head and the nominal speed are each marked at 100 %. The pump characteristic curve is drawn for several speeds in increments of 10 % down from the nominal speed. The system characteristic curve begins at the origin of the H/Q diagram since this is a closed system. Its path is parabolic. The flow rate of the pump is divided into a useful and a bypass flow rate.
Both flow rates can vary from 0 – 100 % and always add up to 100 %. This means that the system characteristic curve is always constant for the pump and that the pump operating point always lies at the design point. If the pump speed is adjusted to the system requirement, the operating point moves downwards along the system characteristic curve in part load operation.

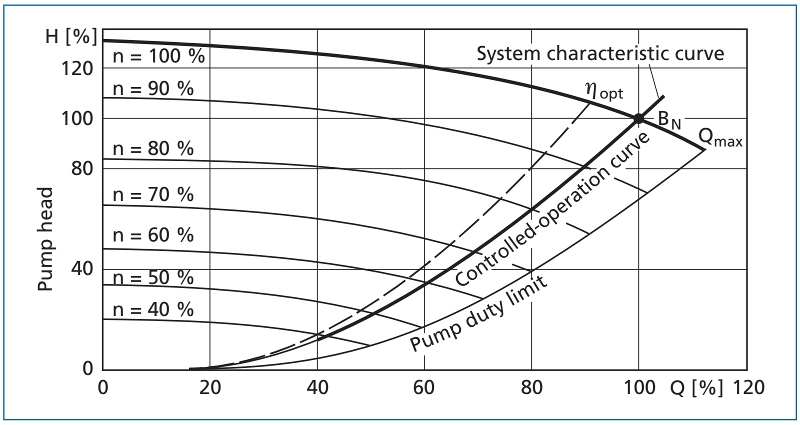


Fig. 40

Note:

In this hydraulic system the (differential) pressure cannot be used as the sole controlled quantity. In this case, pump operation is controlled, for example, as a function of the temperature difference.

Diagram: Pump input power

The pump input power at the design point is 100 %. If there is no speed adjustment the input power remains constant over the whole flow rate range.

The pump input power with speed adjustment is found by drawing lines down from the intersection points of the controlled-operation curve (identical here to the system characteristic curve) with the pump curves at different speeds. Connecting the intersection points yields the shaft power requirement for speed adjustment.

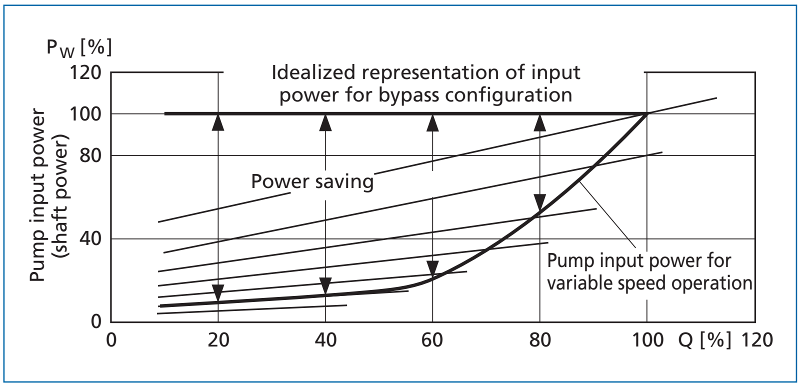


Fig. 41

The power saving varies between the nominal power and the pump input power at minimum speed.

Saving diagram

The saving between the fixed speed and the variable speed shaft power characteristic curve can be clearly seen in the saving diagram. Of the three systems presented, the potential for possible energy savings is the greatest in this case.

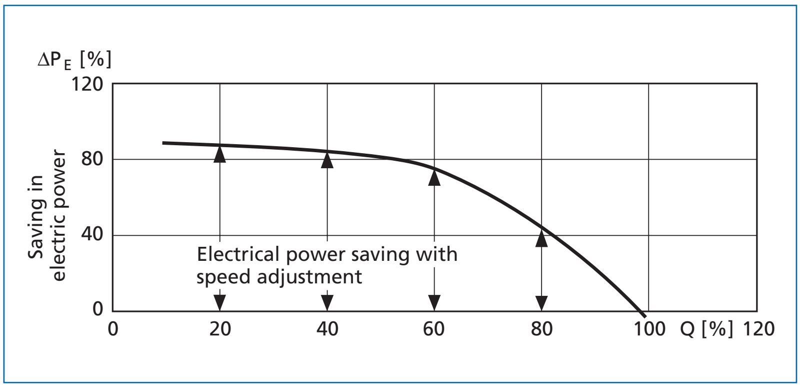


Fig. 42

Economy Calculation

Comparison: Throttling configuration with and without infinitely variable speed adjustment

This is based upon the H/Q diagram (Fig. 43), the power diagram (Fig. 44) for the input power at the pump shaft, the diagram relating to the saving of electric power (Fig. 45) and the load profile (Fig. 46)[1]. Electricity costs are taken to be € 0.10/kWh. The annual load duration curve is converted into rectangular blocks for convenience. In each case the average flow rate over 1000 operating hours is considered. Each average flow rate can be assigned the saved electric power from the saving diagram. In our example,

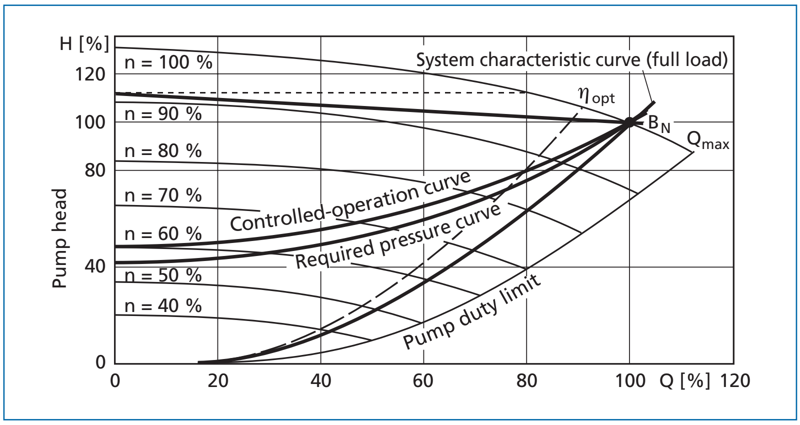


Fig. 43

approximately 50 % of the flow rate is permanently required over 1000 hours; the associated electric power saving averages 38 %. Multiplying the saved electric power with the proportional operating hours and the price of electricity yields the saving for the time period in question. Now we must only add up the proportional savings. The result obtained is a saving of approx. € 232 per year (based upon 1 kW consumed nominal power).

This example was calculated non-dimensionally to improve comparability. Following the same pattern, however, effective figures can also be used in the calculation for each specific application. For example, if the shaft power required at nominal load is 10 kW, approx. € 2320 per year can be saved.

Economy consideration

(based upon 1 kW nominal power consumption)

ΔP_E kW (kW)	B h/a	S Euro/kWh	ΔE_E Euro/a (kW)
0.23	1000	0.10	23.--
0.35	1000	0.10	35.--
0.38	1000	0.10	38.--
0.40	1000	0.10	40.--
0.40	1000	0.10	40.--
0.40	1000	0.10	40.--
0.40	400	0.10	16.--
			Σ 232.--

ΔP_E : Saved electric power
B : Operating hours
S : Electricity costs
ΔE_E : Saving in electricity costs
$\Delta E_E = \Delta P_E \cdot B \cdot S$

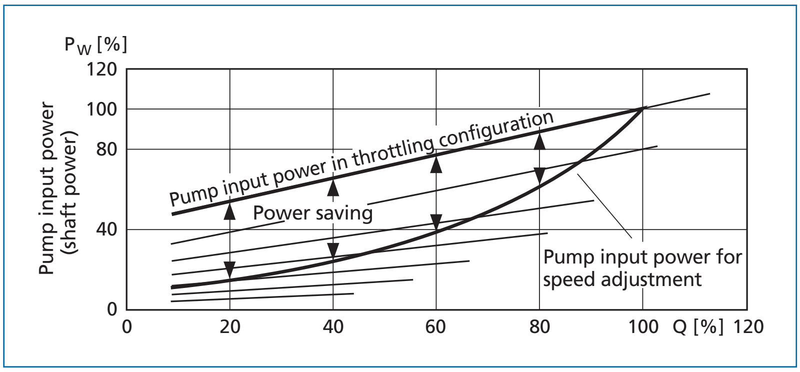


Fig. 44

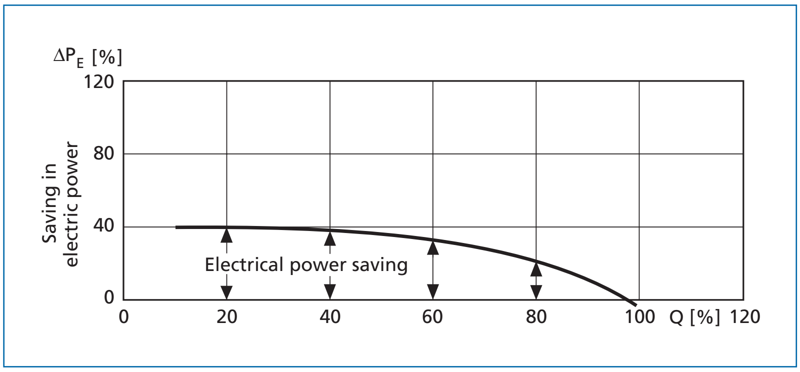


Fig. 45

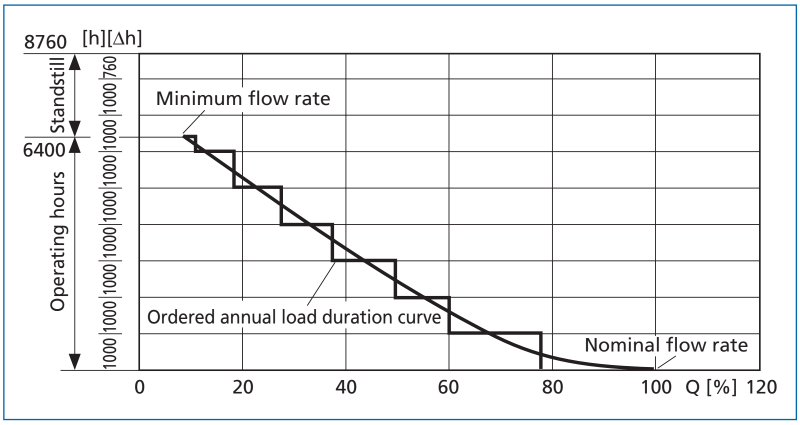


Fig. 46

Note: The calculation performed here is based upon a 100% correct piping calculation and pump design. In practice, however, pump power is often greatly overdimensioned. Consequently, the saving is correspondingly even greater.

1) In the saving diagram (Fig. 45) the motor efficiencies in fixed speed or variable speed operation are taken into account, plus the frequency inverter efficiency in variable speed operation. The flow rate requirement of the pump system over the course of a year – arranged in size order – is entered in the load profile (Fig. 46). This curve is called the “ordered annual load duration curve”. The longer the operating time and the larger the area above the curve, the greater is the possible energy saving potential.

1.2 Control Principles

1.2.1 Definition

Closed-loop control is a process in which the quantity to be controlled (e.g. the level in the high-level tank) is continuously measured and compared with a set value (desired level).

If the comparison yields a difference between the set value and the measured actual value of the controlled quantity, the manipulated quantity (here: pump speed) is automatically adjusted and the control deviation (control error) is rectified. This process is self-contained, therefore we speak of a closed control circuit.

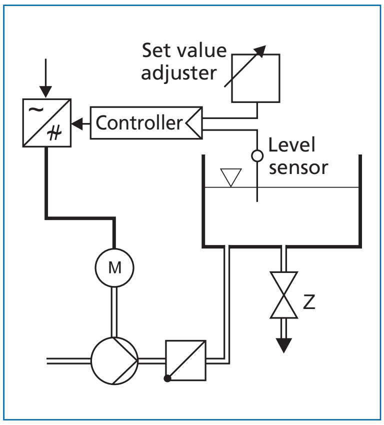


Fig. 47

1.2.2 Further Control Terminology

Open-loop control

is a process in a system, in which one or more quantities in the form of input quantities influence other quantities in the form of output quantities due to the system's inherent properties – open sequence of effect.

Controlled quantity x

is the quantity that should be held constant

Set value X_S

Constant leading value. Set value in fixed point control.

Manipulated quantity y

is the quantity with which the controlled quantity is influenced as desired (e.g. speed).

Interference quantity z

is the quantity that changes the controlled quantity unintentionally from outside (e.g. variable throughflow).

Controlled system S

is the part of the system in which the controlled quantity should be held constant (all components between point of adjustment and point of measurement).

Actual value x

is the momentary value of the controlled quantity (e.g. differential pressure measured using feedback value transmitter).

Leading value w

Variable set value (e.g. managed via external temperature or flow rate or timetable).

Deviation (Control error)

$x_w = x - w$

Deviation from the leading value (from the set value).

Measurement location

is the position in the system where the controlled quantity is measured.

Actuator

Is the device that changes the manipulated quantity (e.g. pump, valve).

Actuating drive

Drive of the actuator (e.g. electric motor, frequency inverter).

Feedback transmitter

Converts the controlled quantity into a standardized electric signal (e.g. 0/4 - 20 mA or 0/2 - 10 V).

1.2.3
Control Terminology Based upon the Example of Pump Control

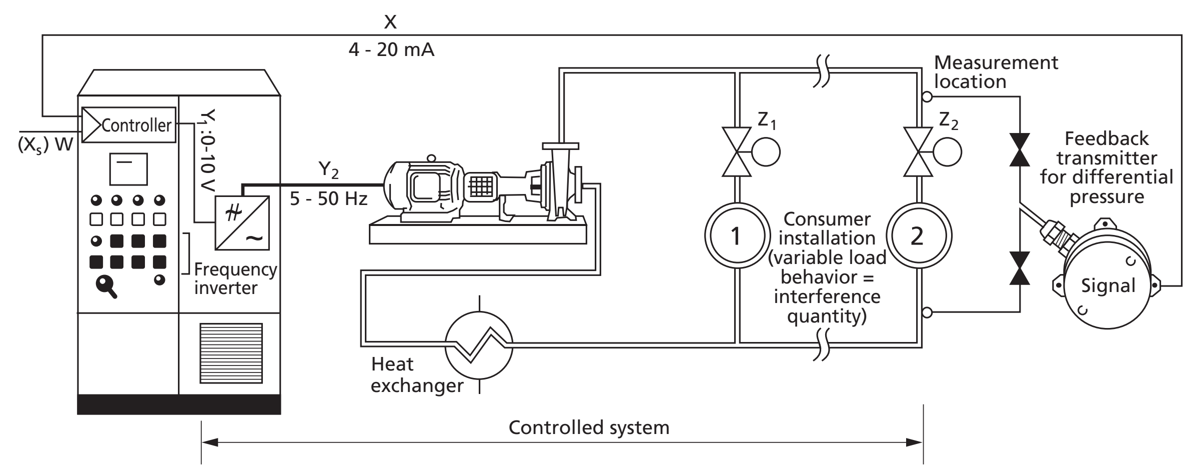


Fig. 48

1.2.4
Controlled Quantities for Closed Hydraulic Circuits

Differential Pressure Dependent Control

If the volumetric flow is variable the differential pressure is the correct controlled quantity. The fact that pressure changes in water-filled pipelines propagate at a speed of approx. 1000 m/s means that a change in differential pressure is reported almost without delay. As a result, the pump can quickly react to the different loads by changing its speed.

In a closed circuit the pump only acts against flow resistances. Geodetic pump heads or the system pressure may not be taken into account. These influences can easily be eliminated if the differential pressure is used as the controlled quantity.

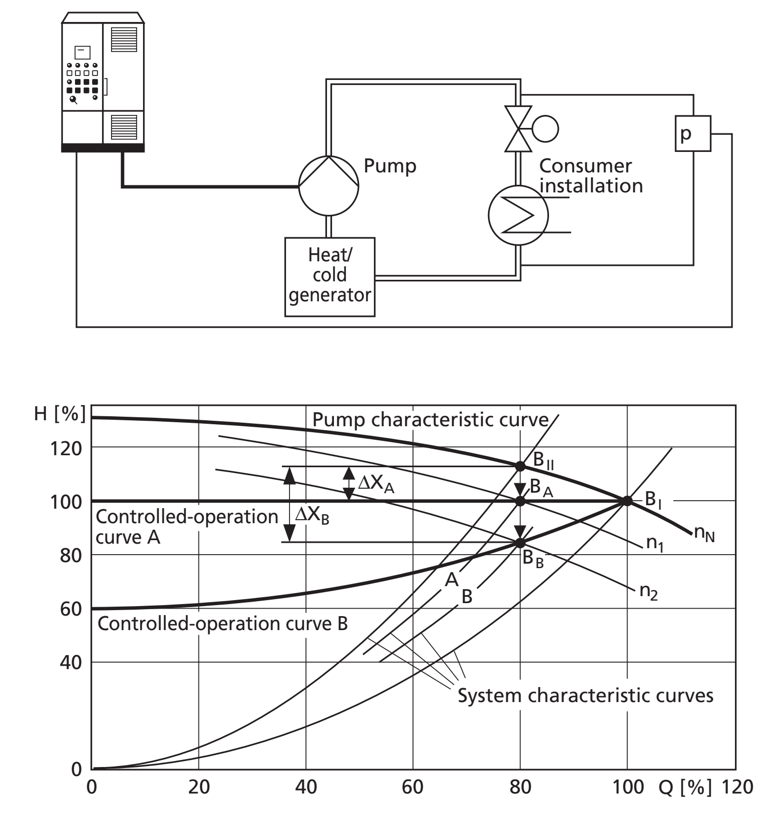


Fig. 49

In Fig. 49 the flow rate is reduced from 100 % to 80 % by throttling. At fixed pump speed the operating point moves from B I to B II. If the measurement point is at the pump, the controlled-operation curve is a straight line that corresponds with the controlled-operation curve A (see Chapter 1.2.6). In our example this means that a differential pressure increase X_A takes place, which is controlled by reducing the speed from n_N to n_1. The new operating point then lies at B_A. For flat pump characteristic curves (e.g. design point in the part load range) X_A may be too low for a fault-free control process.

The following measures may help to rectify this:

1. Putting the design point in the back third of the pump characteristic curve.
2. Using a pump with a steeper characteristic curve.
3. Moving the measuring point away from the pump into the system.
4. Inputting a leading value, e.g. the flow rate (or the external temperature in heating systems) in addition to the differential pressure measurement.

Measures 3 and 4 give rise to a controlled-operation curve with a quadratic path, such as controlled-operation curve B, for example. In the example given the differential pressure deviation corresponds with the quantity X_B. The operating point for variable speed pumps then lies at B_B with the speed n_2. For further details see page 40, "Measuring Location". Even for a very flat pump characteristic curve the reduction of the flow rate to 80 % (in controlled-operation curve B) leads to a deviation (X_B - X_A), which then facilitates a correction (to n_2).

Furthermore, measures 3 and 4 have additional positive effects:

- The speed n_2 is significantly lower than n_N and n_1
- The excess differential pressure, which must be destroyed in the valves, is lower.
- The power consumption falls more significantly.

Applications:

Use in circuits with variable flow rate (by throttling at consumer installations), e.g. in:

- Two-pipe heating-cooling systems with thermostatic valves
- Primary circuit for the supply of district heating transfer stations
- Air conditioning / ventilation systems

Note:

Do not use in circuits with a constant flow rate, such as:

- Single-pipe heating systems
- Consumer-side pumps in return mixing / injection type circuits, in which no throttling takes place on the consumer side.

In differential pressure control for heating pumps we currently differentiate primarily between the control methods Δp constant and Δp variable.

Control method Δ_p constant

The electronics holds the differential pressure generated by the pump constant over the permissible flow rate range at the set differential pressure value H_S.

Applications:

In two-pipe heating / cooling systems with thermostatic valves that have high load authority (previously gravity systems), generously dimensioned systems (resistance of piping small compared to the resistance of the thermostatic valves).

Floor heating with individual room temperature control.

Control method Δ_p variable

The electronics changes the differential pressure to be maintained by the pump linearly. The set differential pressure value is automatically reduced as the pump flow rate falls. This again offers the opportunity of reducing energy consumption.

Applications in two-pipe systems:

With thermostatic valves with low load authority, e.g. tightly dimensioned systems (resistance of pipe similar to the resistance of thermostatic valves, in systems with a very long distribution line).

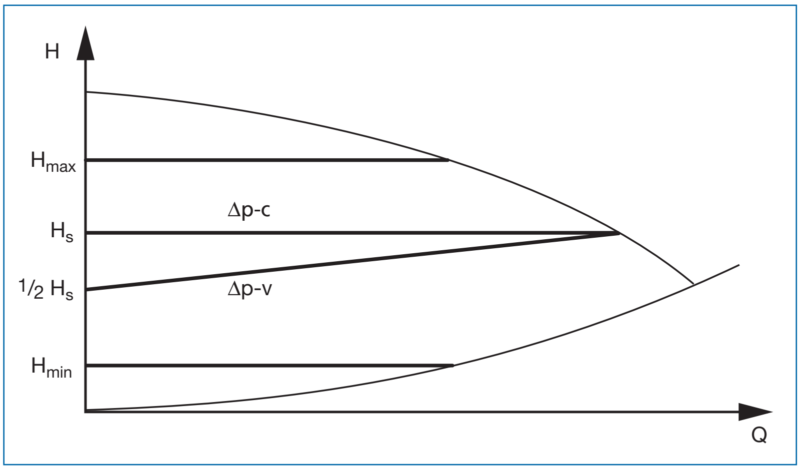


Fig. 50 Control methods Δp-constant and Δp-variable

Optimal control method:

Constant differential pressure at the point of lowest differential pressure (not easily realizable).

Simple alternative:

Constant differential pressure Δp-c at the pump.

Problem:

If noise occurs at low throughflow despite **Δp-c**, **Δp-v** can be selected.

Δp-v offers an extension of the control range with additional savings potential.

Caution:

Undersupply may occur if Δp-v is used.

Differential Temperature (ΔT) Dependent Control

The differential temperature dependent control of pumps is demand-dependent and independent of the operating point of the pump. Its use is worthwhile in situations where the piping characteristic curve is not variable (system sections with largely constant volumetric flow).

The temperature differential between supply and return captures the load state (demand at the consumer installations) directly.

The following applies:

- Full load output of the pump only at max. heat consumption.
- Automatic speed and flow rate reduction in the event of falling temperature difference and at the same time a reduction in pump input power.

Due to the **transport times** of the conveyed fluid long **idle times** may occur, which can impair fault-free control. The use of additional measures, such as **secondary differential pressure control**, allows such systems to be controlled.

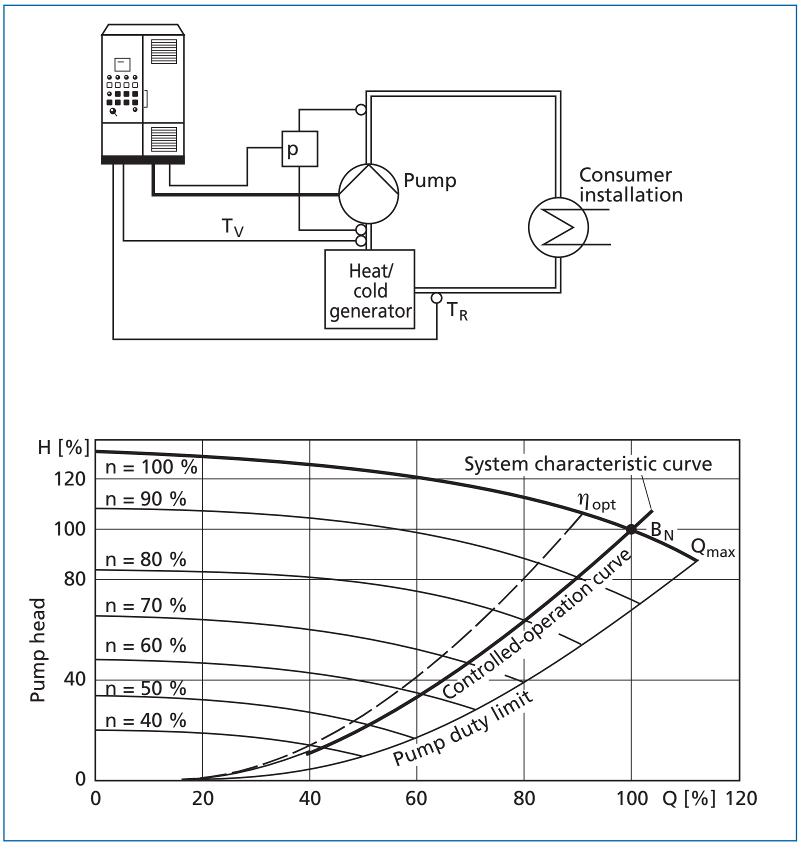


Fig. 51

Applications:

Use in circuits with a largely constant flow rate and constant or variable supply temperature, e.g.

- On the primary side
  - Changeover
  - Injection circuit
  - Low differential pressure manifold
- On the secondary side
  - Return mixing circuit and injection circuit (without consumer-side throttling)

Note:

Do not use in circulation systems (e.g. in heating systems) with a variable flow rate.

Since during throttling the heating medium in the heating unit cools off more quickly as a result of the longer transit time. The higher temperature differential leads to higher speed, which however leads to the reversal of the desired effect, since throttling means that less heating power is required and therefore a lower flow rate, less discharge head and reduced speed.

Return Temperature (T_R) Dependent Control

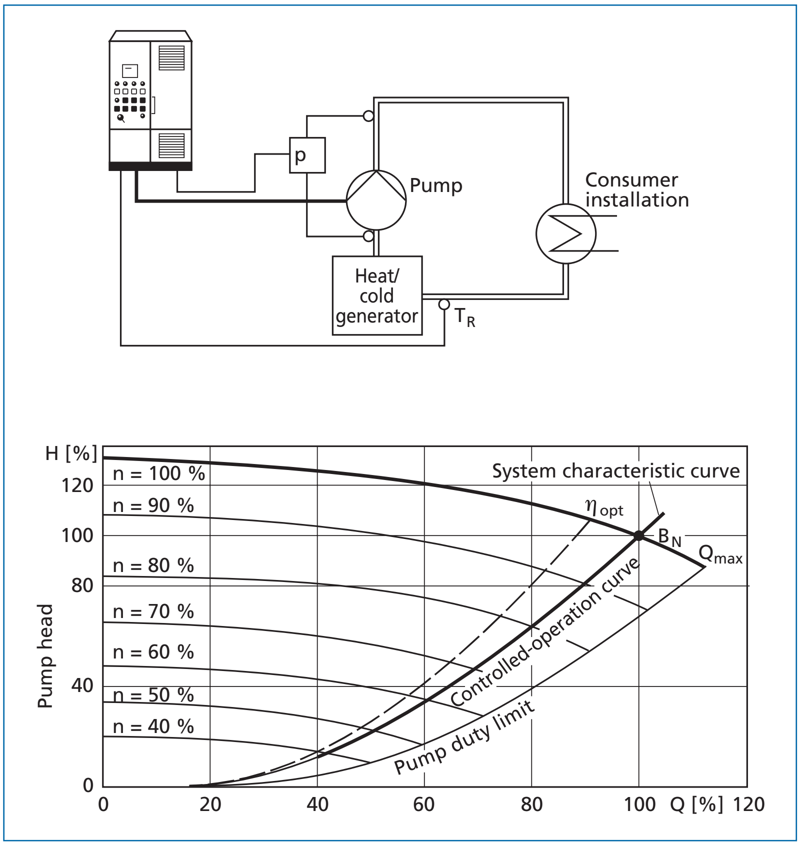
The **return temperature dependent control** of pumps is generally used in heating/cooling systems with heat exchangers that do not use throttling and have a constant supply temperature. The prerequisite is a load-dependent, variable return temperature.

The following applies to pump output control in heating systems:

Low external temperatures
▼
high heat demand
▼
low return temperature
▼
high pump speed
▼
high mass flow rate

High external temperatures
▼
low heat demand
▼
high return temperture
▼
low pump speed
▼
low mass flow rate
▼
low power consumption

In cooling systems the direction of action of the control system must be reversed, i.e. at low return temperatures – low pump speed, at high return temperatures – high pump speed. The purpose is to keep the return temperature largely constant. This achieves a reduction to the required level of the mass flow to be circulated, particularly in part load operation. The heat losses in the return line are reduced as a result of the reduced return temperature. This working principle creates the best preconditions for modern condensing heat generators.



Applications:

Well suited for systems without throttle units and with a constant supply temperature.

Note:

- **A minimum circulatory flow rate must always be guaranteed for reliable function (see Fig. 2).**
- **The operating limits for the cold/heat generator must be adhered to.**

Supply Temperature (T_V) Dependent Open / Closed Loop Control

The supply temperature dependent open-loop control of pumps is primarily used in heating systems with a constant volumetric flow and it can be used in almost any such system. The prerequisite is a supply temperature controlled by atmospheric conditions based upon an automatic mixing configuration or a low-temperature boiler with temperature adjustment option. The flow temperature is thus matched to the system load. The pump speed and thus the flow rate are adjusted according to the supply temperature:

Low external temperatures	High external temperatures
▼	▼
high supply temperature	low supply temperature
▼	▼
high consumption	low consumption
▼	▼
high pump speed	low pump speed
	▼
	low pump power consumption

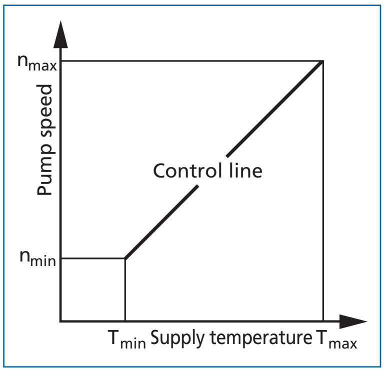


Fig. 53

Apart from the supply temperature dependent open-loop control described above there is also supply temperature dependent closed-loop control, in which the supply temperature should be held constant. This is the case in heat recovery systems, for example. In such systems the supply temperature is to remain constant despite the varying incoming heat. This means, at higher available heat the pump speed increases, at lower available heat the pump speed falls.

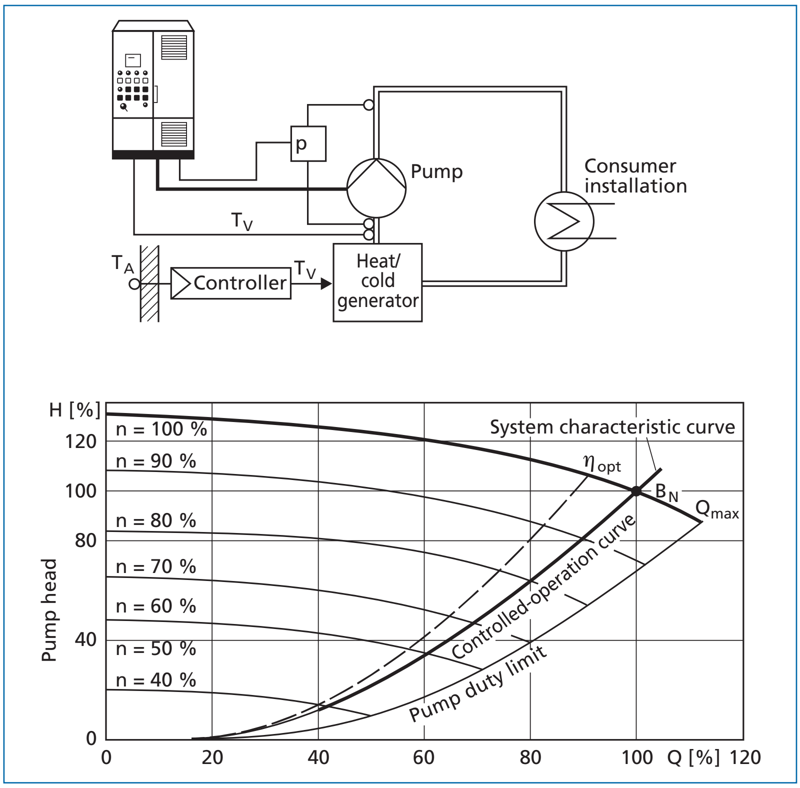


Fig. 54

Applications:

In all systems, in which the supply temperature is set in relation to the load.

The supply temperature dependent open-loop control of the pump flow rate supports this regulatory function.

Particularly in part load operation, a larger opening stroke of the control valve is achieved, which gives rise to better stability of the temperature control circuit.

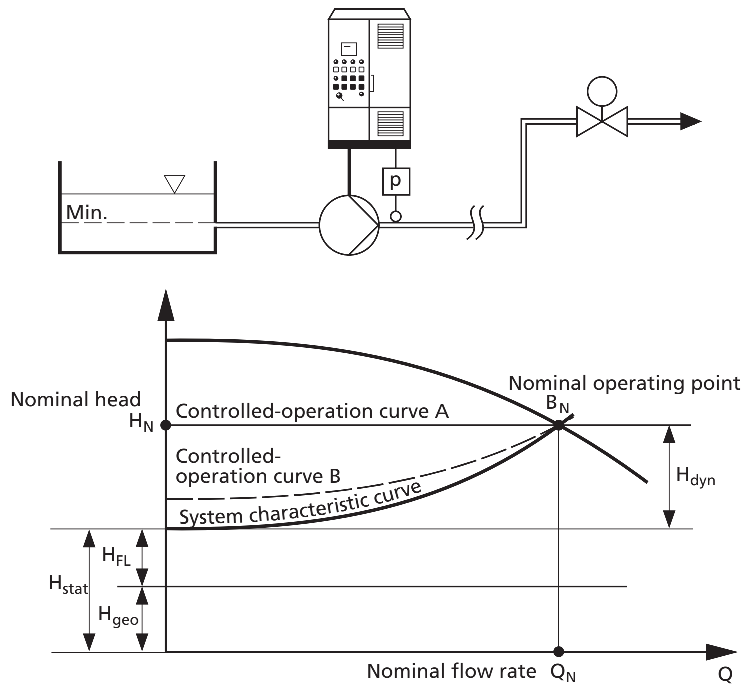
Note:

A minimum circulatory flow rate must always be guaranteed for a reliable function (see Fig. 2).

1.2.5 Controlled Quantities for Open Circuits

Pressure Dependent Control

Pressure dependent control is particularly suitable for open systems with variable volumetric flow. This is brought about by various withdrawal rates (throttling) at the consumption points. The task of the variable speed pump is to supply sufficient pressure (flow pressure) to the consumption points. Due to the varying volumetric flows, variable pressure losses occur in the transport pipes. If the measuring point lies at the pump, the controlled-operation curve has a constant (horizontal) path. Good pressure control generates only the level of pressure that is required in the load state in question. This can be achieved by a suitable selection of the pressure measurement location in the system a long way away from the pump or by intelligent pump control systems (controlled-operation curve B).



H_{FL}	Flow pressure (desired pressure at consumer installation)
H_{geo}	Geodetic head (from water level to water level)
H_{dyn}	Dynamic head component (pipe friction losses)
H_{stat}	Static head (head component of the system that is independent of Q)

Fig. 55

Applications:

- **Water supply systems**
  Drinking water
  Pressure boosting
  Fire extinguishing systems
- **Industrial processes**
- **Cooling systems**

Note:

The influences of any variable inlet pressure and difference in geodetic head or counterpressures must also be taken into account in the design of pumps and control systems.

Level Dependent Control

If a constant liquid level is required in a tank the level is usually the suitable controlled quantity. Changing the supply or discharge brings about a level deviation. When the target level is exceeded the speed increases (the pump conveys more), when the level drops below the desired value the speed falls (the pump conveys less). The pump pressure is only high enough to compensate for the differences in geodetic head and the frictional losses. At constant geodetic head and unchanged piping there is a quadratic H/Q curve.

The increase corresponds with pipe friction losses, which rise with the increasing flow rate. The set value H_{set} is found from the desired level in the tank.

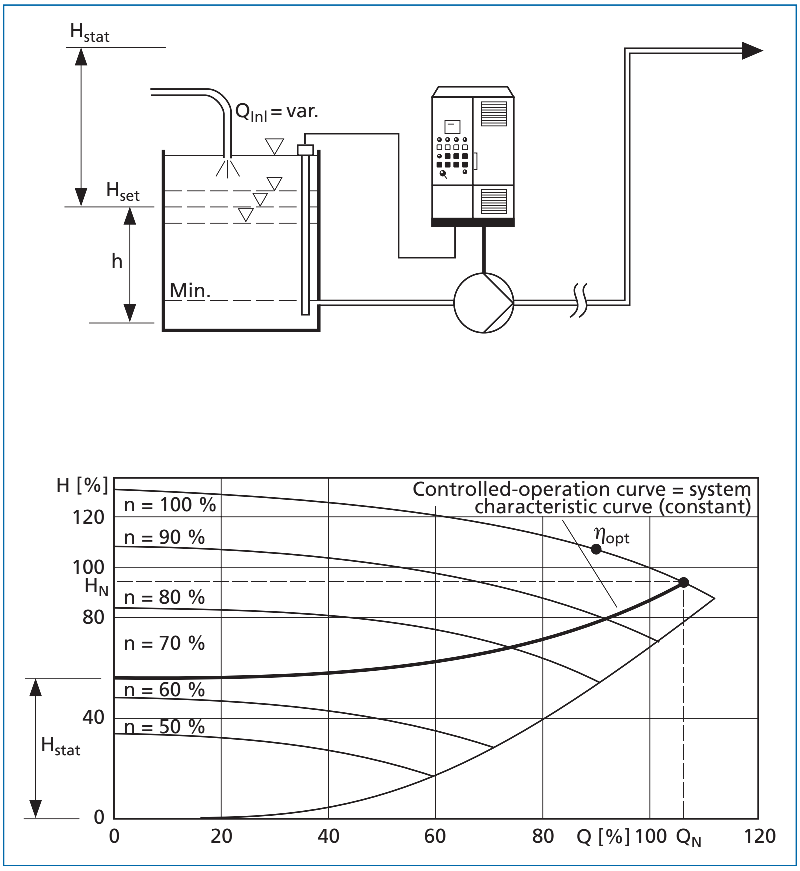


Fig. 56 Drainage system

Applications:

e.g. in

- **Waste water treatment**
- **Cooling water systems**
- **Process technology**

In the design of the pump/transport concept attention should be paid to the combined effects of, and interaction between, the following variables:

Supply, discharge, tank switching volume, pump size, control speed.

Note:

In addition to the signal transmitter required for system control, devices that protect the tank against overflowing and stop the level from falling below the minimum level must also be provided in the tank.

These protective devices should always be independent of the control system's signal transmitter (in the simplest case by means of separate float switches).

If there is a danger of blockages or operating errors it is recommended that the pump flow rate is also monitored.

If the total flow rate is split between several pumps (peak load pumps), particular attention should be paid to the operating method of the control system.

Flow Rate Dependent Control

The objective of this is to hold the flow rate at a desired value. Interference factors, such as fluctuating inlet pressure or resistance (e.g. due to dirty filters) must be compensated. The H/Q curve / controlled-operation curve should be a vertical line on the H/Q diagram.

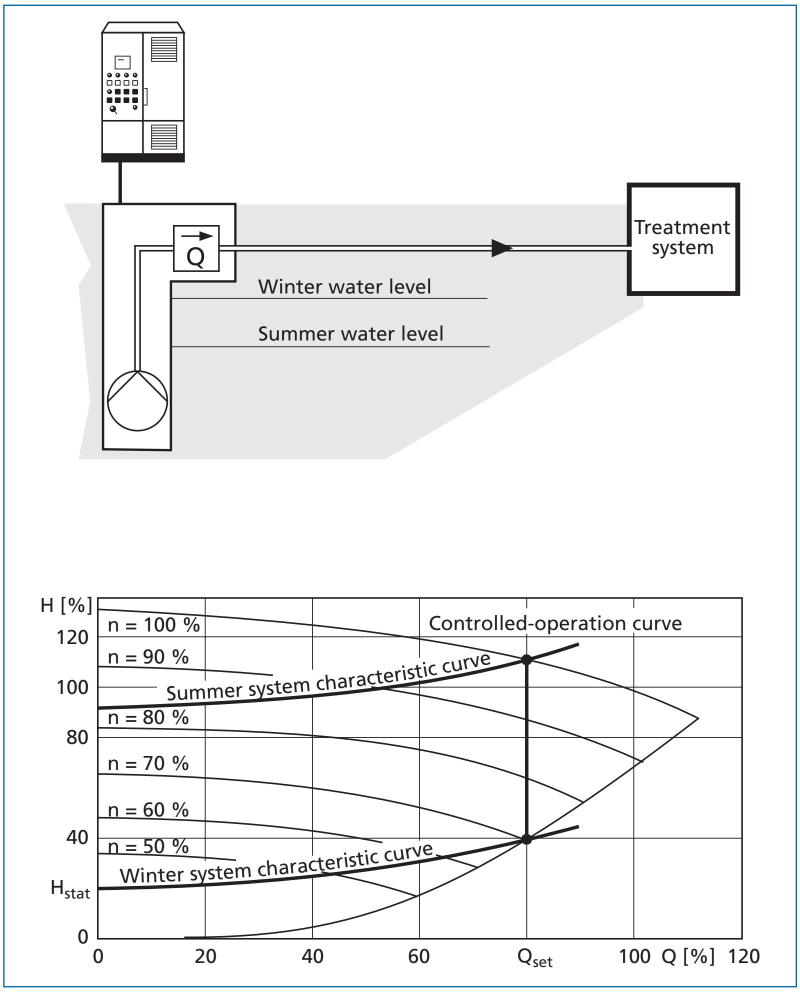


Fig. 57 Water treatment system

Applications:

- Water treatment systems
- Cooling processes
- Mixing tasks
- Waste water treatment

Note:

The influences of any inlet pressure variations, geodetic head differences or counterpressures must also be taken into account in the design of pumps and control systems.

Flow (rate) transmitters shall be selected in accordance with the requirements of the fluid and the external operating conditions.

1.2.6
Compensation of Additional Interference Factors

The task of the control system is to manage the process optimally. To this end the effects of the main interference factors must be offset. In the following two examples the throttling behaviour of the consumer installations represents the main interference factor. The variable volumetric flow results in different pipe friction quantities. Two possibilities for offsetting this additional interference factor are described below.

Compensation by the Selection of the Correct Measurement Location

We will now highlight the influence of the measurement location on pressure / differential pressure control using an example from heating technology. The positioning of the measuring point has a decisive influence upon the pressure conditions and the operating costs of the system. If the differential pressure transmitter is fitted in the immediate vicinity of the pump, then at loads less than 100 % the system will operate at an excessive differential pressure. Power consumption is greater than necessary.

More favourable conditions exist if the measuring point is fitted a long way from the pump in the supply network.

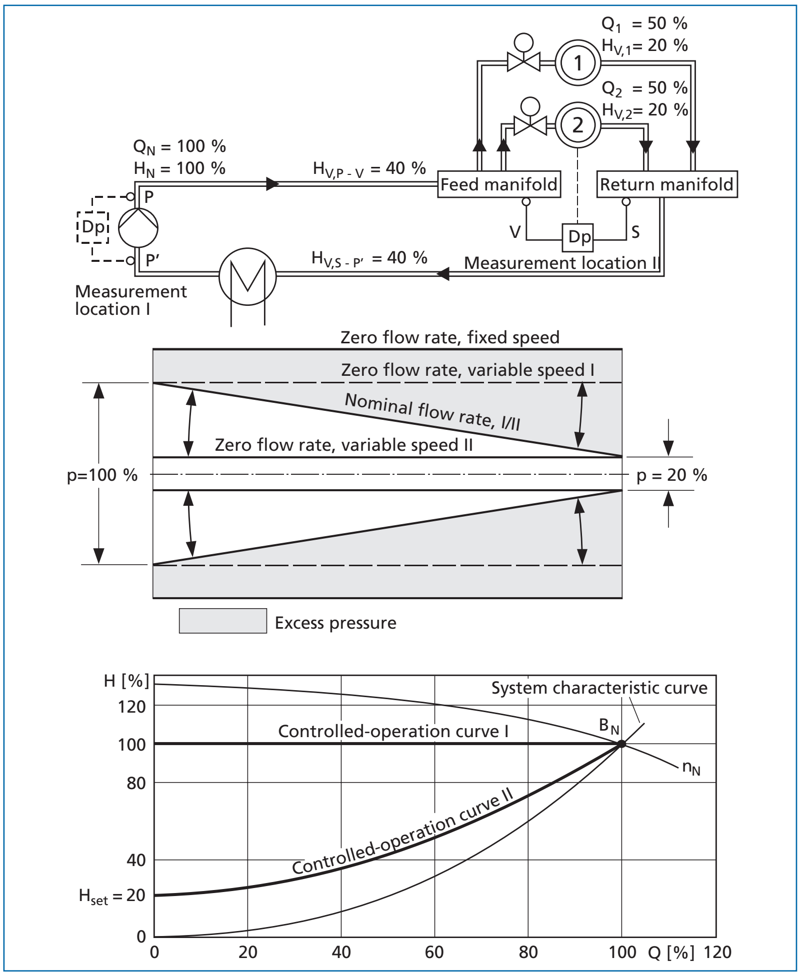


Fig. 58 Influence of measurement location on pressure / differential pressure control

System layout

Two consumer installations are present, which are each designed for half the nominal flow rate. The consumers are supplied by a pump which is suitably dimensioned for the nominal flow data. The figures in the H/Q diagram are shown in non-dimensional form and relate the design data. Nominal flow rate and nominal head are each 100 %. The location for measuring pressure / differential pressure may lie at the pump or near the consumer installation, as desired. In the example it lies close to the pump, between suction and discharge side (measuring location I), or between the feed and return manifolds (measuring location II).

In open systems (e.g. water supply) pressure is measured instead of differential pressure. Here too the measuring location can be near to the pump (discharge side) or near to the consumer installation.

Key to index:

N	= Nominal
V	= Feed manifold
P	= Pump
S	= Return manifold
P-V	= Section Pump – feed manifold
S-P	= Section Return manifold - pump

System characteristic curve

Development:

Pressure losses in the pipeline sections are plotted over the flow rate. If the flow rate increases linearly the pressure loss increases quadratically. Parabolas are formed in the H/Q diagram.

In Fig. 59 the consumer circuits are connected in parallel, so that flow rates of equal pressure are added. This yields the summed characteristic curve for the two consumers.

In Fig. 60 the consumer circuits are connected in series. This means that the resistances of the individual flows are summed.

The final system characteristic curve is found by adding the summed characteristic curves of the consumer resistances to the resistances of the main circuit.

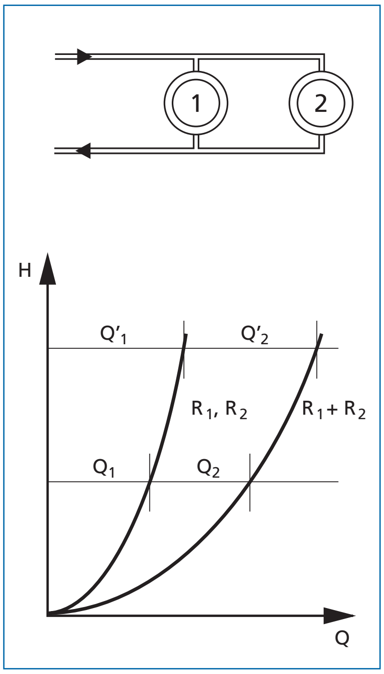


Fig. 59 Parallel connection

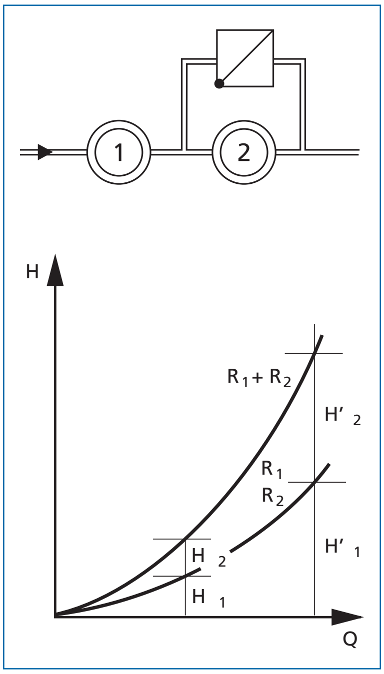


Fig. 60 Series connection

The required pressure curve

Measurement location II

There must always be a sufficient pressure difference between feed and return manifold, so that the consumer installations are always adequately supplied. Depending upon the consumer installation in question, various load states can exist. For example, each consumer installation could be loaded at between 0 - 100 % independently of one another.

To ensure that the consumer installations are adequately supplied at all times, in the example shown the required pressure path is assumed to be such that at least the nominal pressure requirement of the consumer (here H_{set}) exists between feed and return manifold.

If both consumer installations are closed ($Q/Q_N = 0$) there is no flow, and thus no flow losses. The pump works at such a low speed that the set value (Hset) is just maintained. If a consumer installation is opened there is a flow in the main pipelines accompanied by pressure losses. However, in order to be able to maintain the set value, the pump must increase its speed and generate more pressure. Since the pressure loss increases quadratically in relation to the flow rate, the controlled-operation curve II takes on a parabolic shape. The pump generates only as much additional pressure as is necessary to compensate for the dynamic pressure losses that arise.

This is also particularly clear in the pressure diagram. The pressure between feed and return manifold is constant and increases continuously over the length of the main pipelines to the pump depending upon the flow rate (up to the nominal flow rate at nominal heads). Pump control (pressure / differential pressure control) is optimal if the controlled-operation curve lies on or only slightly above the required pressure path.

Measurement location I at the pump

If the differential pressure is measured at the pump, the target value must be set at the nominal head. In the H/Q diagram this means that the pump pressure is constant over the entire flow rate range (horizontal controlled-operation curve I).

We see that, particularly in low part load operation, the generated pump pressure lies above the required pressure path.

In the pressure diagram the pressure is constant at the pump and decreases along the main pipelines depending upon the flow rate.

We see clearly here that despite speed control the pressure is too high at the feed manifold in part load operation. This excessive pressure can have an unfavourable effect upon the consumer behaviour. In any case, however, too much pump energy is expended.

Compensation by means of Additional Measured Variable (Flow Rate)

For various reasons it is not always possible to measure a long way from the pump and near to the least favourably situated consumer installation. This applies to district heating systems, where very long distances have to be bridged or, for example, systems that are constructed according to the plan in Figs. 61 and 62.

By combining pressure and flow rate detection, both variables can be measured directly at the pump.

The objective here is to obtain a controlled-operation curve with a quadratic path (see also Fig. 58 – controlled-operation curve II, also called DPC curve).

DPC: Dynamic pressure compensation (Pressure control with flow rate dependent set value readjustment)

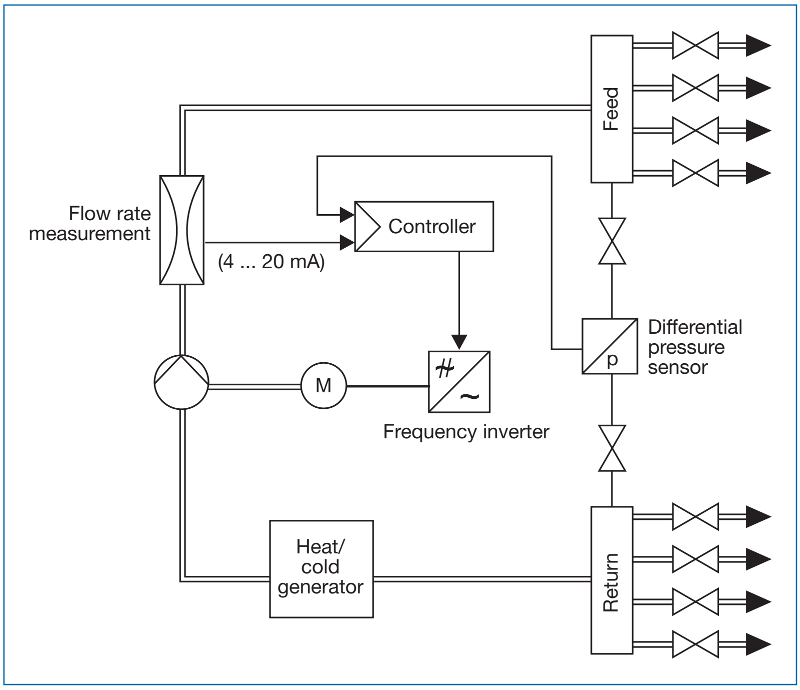


Fig. 61 Flow diagram of a heating system

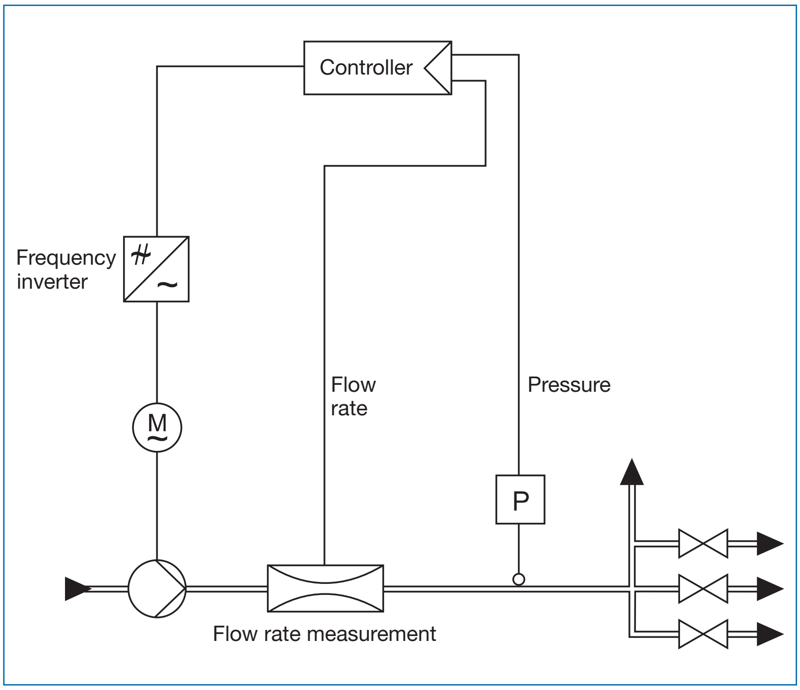


Fig. 62 Flow diagram of a transport system (open)

Applications:

- In building restoration with insufficient system data
- In the event of undersupply in various load states (by variable controlled-operation curve)
- In the event of long signal transfer distances

Note:

Modern control systems are capable of calculating the optimal controlled-operation curve automatically.

This requires the following operating data

- Nominal head
- Nominal flow rate
- Pressure requirement of the consumer installation.

This is also possible without flow rate measurement.

1.3 Principles of Integral Drive

1.3.1 "Intelligent" Integrated Drives for Pumps

An integrated drive for pumps is a compact drive system that consists of a motor (el. machine), an energy adjusting element (frequency inverter) and a microcomputer for open and closed loop control. Fig. 63 shows such an "integral drive" and its process.

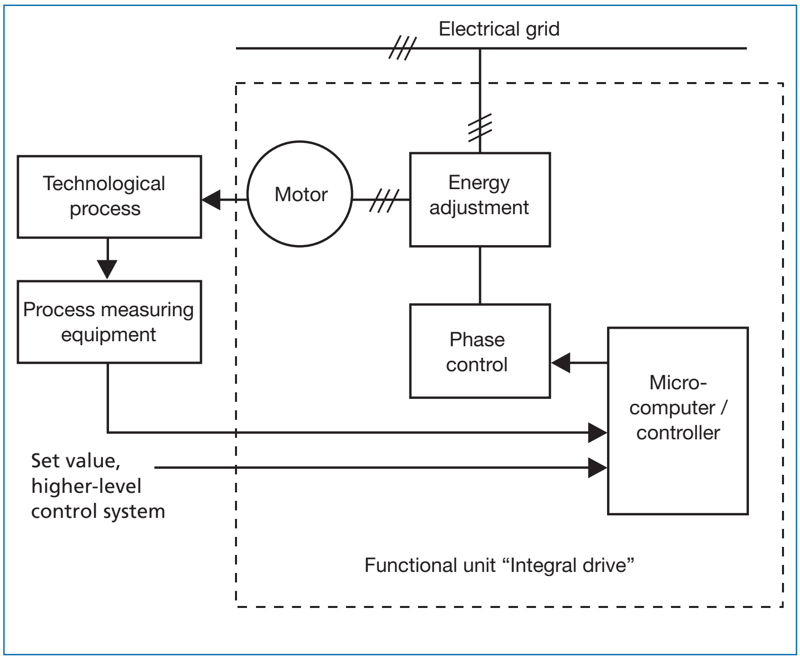


Fig. 63 Integral drive and process

1.3.2 Advantages of Integration

The integration of the energy adjusting element (frequency inverter) and motor is associated with many advantages:

- **Simple commissioning, since the motor and inverter parameters have already been set in advance at the factory.**
- **Cables between frequency inverter and motor are dispensed with, leading to a reduction in the electrical load on the motor, less EMC problems**
- **Integrated control functions, no external control device necessary**
- **Reduced fitting costs compared to conventional solutions**
- **Significantly fewer wiring errors**
- **EMC filter already integrated into the drive**
- **Integrated pump and motor protection**

1.3.3 Requirements

The following points can be listed as requirements for intelligent integrated drive systems:

- Economical fluid transport based on actual demand as a result of speed adjustment
- High reliability and availability
- Mechanical compatibility to IEC standardized motors
- Electromagnetic compatibility
- Simple modification to the application by on-site parameterization option
- Extremely simple operation, local or remote controlled
- Integrated drive protection and fault diagnosis functions
- Pump-specific control functions
- Interfaces for communication with higher-level systems (pump control technology)
- Decentralized "intelligence"

The term decentralized "intelligence" is used to mean the capability of a pump drive to adapt itself to changed process requirements. It must be capable of monitoring itself and the pump, communicating with the environment digitally, and if required both reacting and acting independently.

1.3.4 Pump-specific Functions

In addition to open and closed loop control, other important functions for integrated pump drives include dynamic pressure compensation, a memory function, minimum flow tripping, dry-running protection, inertia-secure start function and real time clock functions.

- Due to dynamic pressure compensation in variable speed operation, pipe friction losses can be compensated when a pressure sensor near the pump is used, so that pressure remains constant at the consumer installations.
- A memory function records the power input curve with a closed pump discharge side throttle. This data is required to activate the “minimum flow tripping” and “dry-running protection” functions.
- Minimum flow tripping (energy saving function) ensures that in closed loop control mode the drive is switched off as soon as the flow rate falls below a preset minimum value. This is to avoid wearing out the pump. When demand rises again, the pump is switched back on automatically.
- If the dry-running protection function is activated, the motor is stopped if the power / speed ratio falls below a stored value due to dry-running to protect the pump (mechanical seal) and the system goes into fault mode.

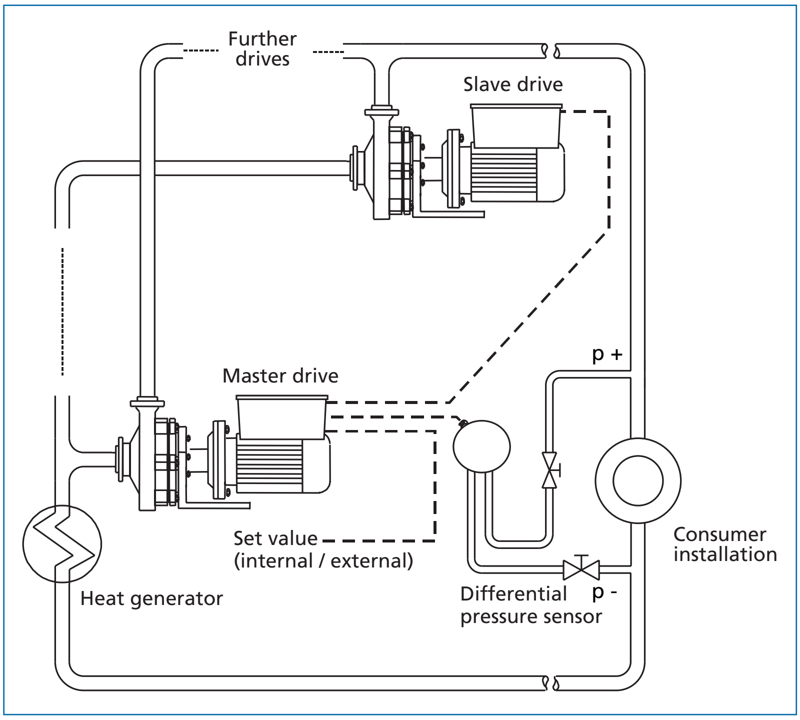


Fig. 64 Pumps with integral drive in a master/slave configuration

- An inertia-secure start function is provided for shaking a blocked shaft loose by generating an alternating torque.
- The internal real time clock of the drive means that time-dependent functions, such as time-of-day and day-of-week programming, pump changeover and night-time setback can be selected.

An integrated pump drive can generally be used as a variable / fixed speed single drive or in Master/Slave mode.

In Master/Slave mode several drives can be operated in parallel. In the event of a fault the master function can be assigned to another drive. The necessary data exchange takes place via an internal bus system. No additional external control equipment is required for this application.

Fig. 64 shows a differential pressure control setup in a heat supply system in which several drives can work in master/slave mode.

1.3.5 Economy / Reduction of Life Cycle Costs

The extra costs for an integral pump drive are, as is the case for other speed-controlled pump drives, recouped after just a few years due to the power saving. Moreover, an integral drive for pumps offers further savings potential.

The following important points can be mentioned:

- Very low installation and commissioning cost
- Low space requirement
- Further power savings possible by minimum flow tripping, time-programming, night setback
- No downtime due to parallel operation of pumps

Due to these potential savings and possibilities offered by a modern integral drive, the integral drive offers clear advantages over conventional solutions with regard to life-cycle costs.

1.4 Principles of Communication Technology

- Modern building management systems are used in large buildings
- Building management systems provide “intelligent” input to the operating systems and technical building equipment
- Building management systems create open communication between the automation and control systems.

The technical building equipment comprises various systems (HVAC = Heating Ventilation Air Conditioning), e.g.

- Heating
- Sanitary (supply and disposal)
- Air conditioning / ventilation
- Electric
- Measurement, open and closed loop control technology

This results in tasks including the following:

- Operations management
- Operations monitoring
- System automation
- Energy management
- Maintenance management
- Data archiving
- Operational analysis

Only by planning that covers all systems can neutral building management systems be created which fulfil the expectations of the operator.

Parallel data transfer (previously)

Simultaneous transfer of information via a large number of parallel lines

Serial data transfer (new)

Transfer of information via two lines. The information is transferred serially in digital form.

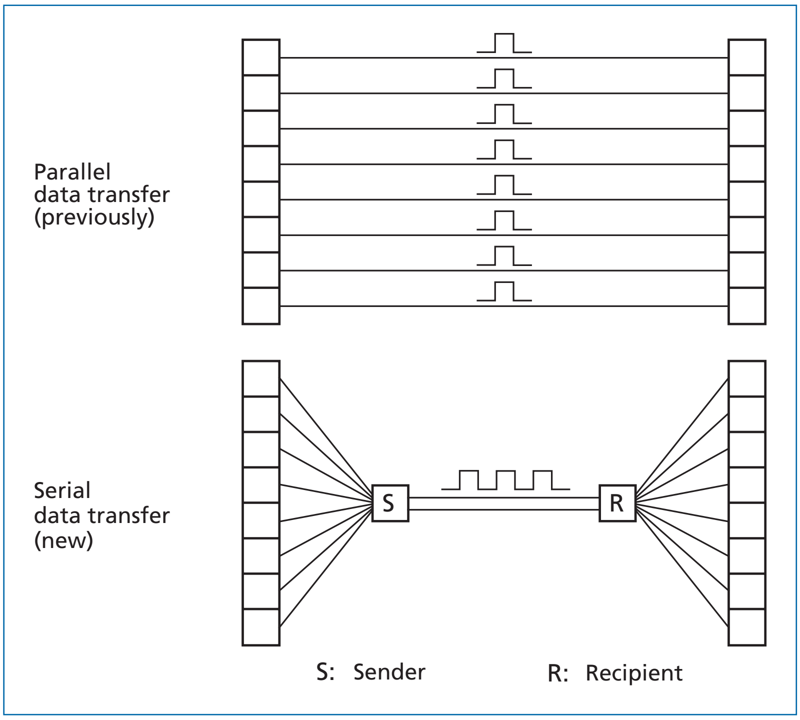


Fig. 65 Parallel and serial data transmission

Levels model of automation

Communication in automation is normally defined using the levels model. The data is transferred vertically via standardized – so-called open – bus systems.

Useful pump data:
- Start/stop
- Set values / actual values
- Speed
- Status reports
- Fault messages

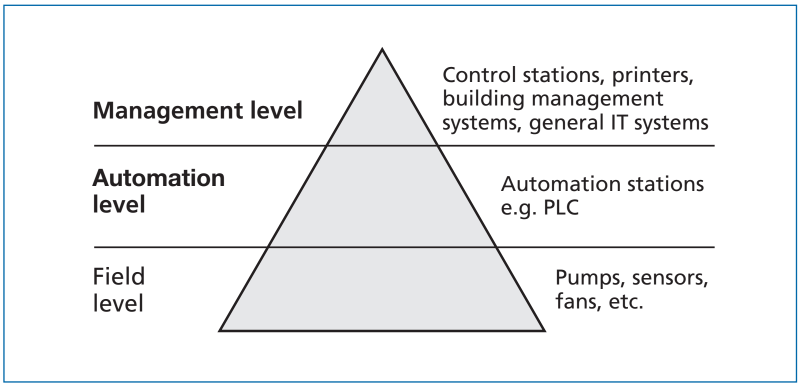


Fig. 66 Levels model of automation

Functions of the levels and relevant bus systems

Level	Task	Bus systems used
Management level	• Information management for entire system • System monitoring • Parameterization of programs • Data protection • Cost allocation	• BACnet • FND
Automation level	• Basic and processing functions • Connection of input and output devices • Performance of complex control processes	• BACnet • World FIB (France) • PROFIBUS • EIB on Automation Net
Field level	• Application specific open/closed loop control • Measured value detection and preliminary processing • Alarm messages • Event messages	• BATIbus } Konnex • EIB } Konnex • EHS } Konnex • LON

Typical communication structure for a pump group

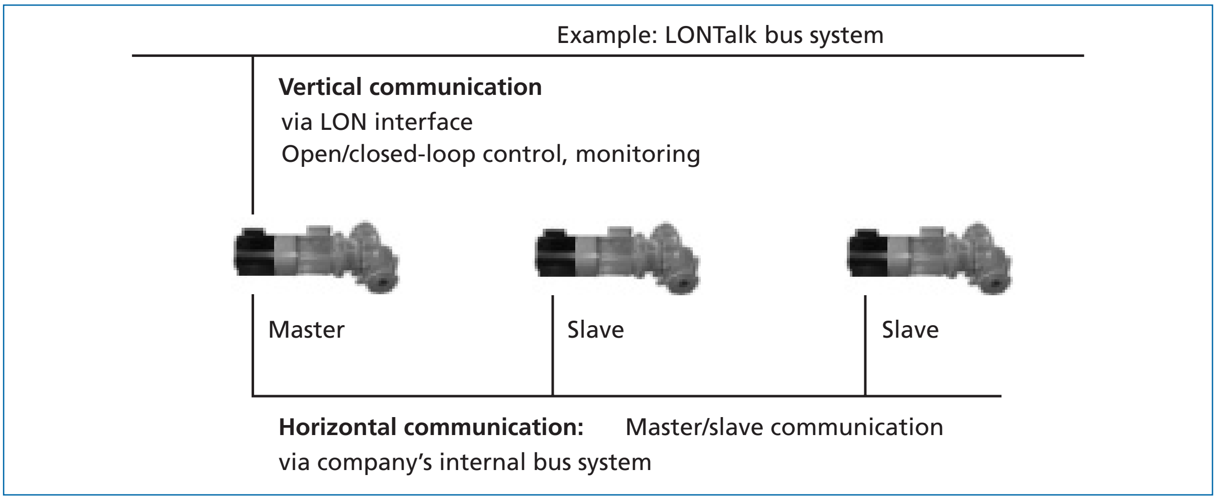


Fig. 67 Communication structure for a pump group

2 System Automation Terminology and Planning Notes

The planning of circuits of all voltage levels covers the collection of operating conditions and the specification of the system concept and the planning principles to be used for implementation. The project planning phase represents a period of intensive co-operation between the principal, his engineering consultant, and the contractor.

The operating conditions are determined by the environmental conditions (place of installation, local climatic factors, environmental influences), the higher-level electricity supply system (voltage level, short-circuit power and neutral-point connection), the switching frequency, the required availability, safety requirements, and specific operating conditions.

With regard to the equipment and system costs every measure must be considered from the point of view of necessity and from an economic point of view.

Pump automation systems today are produced to a standard which can easily be adapted to further-reaching requirements using modern CAD tools.

If a pumping task is to be solved, various operating conditions have to be taken into account, e.g. acquisition and operating costs, operating reliability (stand-by equipment), process conditions, desired operating behaviour, etc.

We can proceed with project planning in the following order:

a) Flow rate to be split between one or more pumps

b) One or more frequency inverters

c) With / without stand-by pump

d) Pump selection

e) Determine shaft power

f) Specify necessary motor power

Regarding a)

The majority of costs for an infinitely variable speed control system are caused by the frequency inverter.

By splitting the nominal flow rate between more than one pump we can significantly reduce the purchase costs, whilst the control convenience remains basically the same. Only one pump is operated through the frequency inverter. Further pumps supplied directly from the grid cut in and out depending upon demand.

Since the pumps deliver into a common hydraulic system, the pressure is determined by the variable speed pump. The operating point moves along the controlled-operation curve.

Regarding b)

If technical requirements are such that the task cannot reasonably be handled by one frequency inverter alone, there is the option of using several duty pumps with several frequency inverters. This makes it possible to manage difficult system conditions (e.g. greatly fluctuating inlet pressures, frequent part-load operation) reliably and economically in addition to achieving increased operating reliability.

Regarding c)

As can be seen from Fig. 77, 75% of the nominal flow rate for this controlled-operation curve is achieved with just one pump. In such a case an additional stand-by pump (3rd pump) is only required in systems in which the full hydraulic power must be available at any time (e.g. service or process water supply).

Regarding d)

The required flow rate Q_N at the nominal operating point can either be achieved using one pump or by two or more pumps in parallel operation. It should be taken into account in the pump selection that the pumps involved must be capable of intersecting the controlled-operation curve. In practice, excessive safety factors in the calculation of the pipeline resistances mean that the pumps may operate outside the permissible operating range.

Regarding e)

Fig. 77, shown below, can be used to determine the pump shaft power requirement.

Based upon the greatest possible flow rate of the base load pump (intersection: controlled-operation curve with pump characteristic curve at max. speed) the necessary shaft power is determined by drawing a line down to the pump power characteristic curve.

Regarding f)

For the necessary nominal motor power (P_2) safety factors of 5 - 10 % should be included in the calculation due to tolerances in the pump and system characteristic curves and additional motor losses due to frequency inverter operation.

2.1 General Electrical Notes

Power Supply System Types

TN-C system

The neutral point of the voltage generator is directly earthed. The housing of the connected operational equipment (control cabinets, motors, etc.) is connected to the neutral point via the combined neutral and protective conductor (PEN).

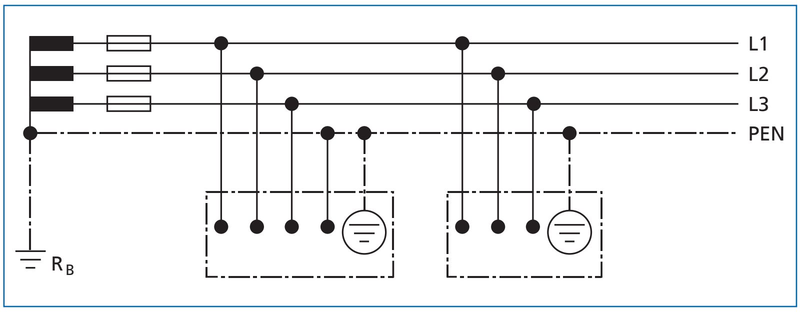


Fig. 68 TN-C system

TN-S system

As above, but protective conductor PE and neutral conductor N are laid separately.

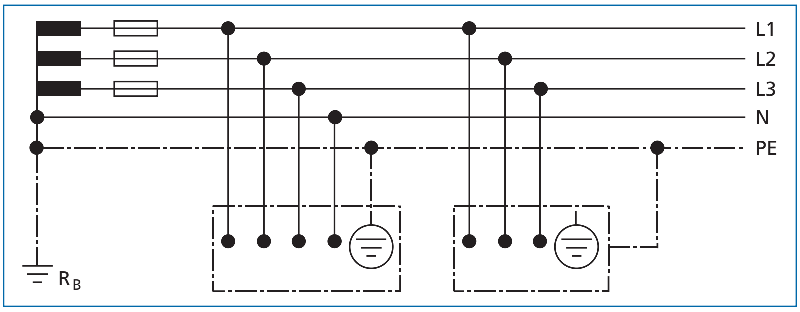


Fig. 69 TN-S system

TT system (common in France)

The neutral point of the voltage generator is directly earthed. The housing of the operational equipment is connected to dedicated earthed electrodes, which are independent of the earthing of the voltage generator.

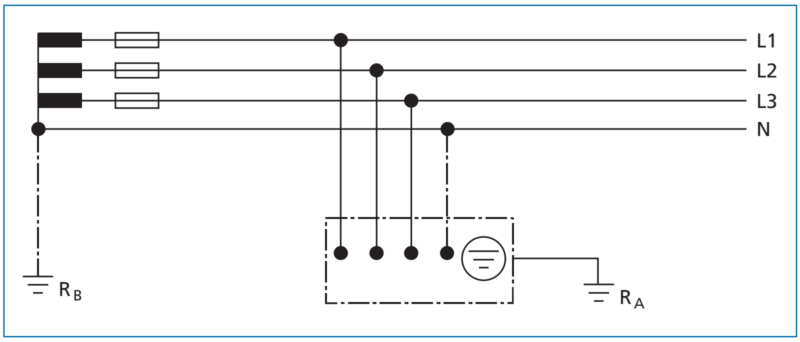


Fig. 70 TT system

Earth Leakage Circuit Breakers (ELCB)

Earth leakage circuit breakers disconnect all poles of operating equipment within 0.2 s as soon as an electric shock hazard occurs due to an insulation fault.

ELCBs are designed for different nominal leakage currents.

Designs with tripping currents of 30 mA also act as personnel protection. At greater tripping currents protection against fires ignited by earth leakage currents dominates.

Devices with rectifier circuits (e.g. frequency inverters), in which direct leakage currents can occur in the event of a fault, may not be operated behind ELCBs. In these cases so-called universal ELCBs (for all types of current) with a higher tripping current are used.

Power System Dependent Protective Measures

Power system dependent protective measures are protective measures using protective conductors. The protective conductor (PE) is connected to the inactive bodies of the electrical operating equipment. Protective conductors and PEN conductors are marked in green/yellow.

In power system dependent protective measures, line-side overcurrent protective devices switch the power off and a fault message is generated in the IT system.

Ambient Temperature

In compliance with the relevant DIN and VDI provisions the following simplified system classification can be made:

- Ventilation devices and systems for aeration and deaeration, e.g. if the permissible ambient temperature is higher than the (maximum) external temperature.
- Cooling devices and systems for pure heat removal, e.g. if the permissible ambient temperature is less than or equal to the (maximum) external temperature.
- Air conditioning devices and systems for the air conditioning of rooms if certain room climatic conditions must be adhered to in addition to heat removal (temperature, moisture, air quality, etc.)

Starting Method (Starting Process) for Squirrel-Cage Motors

Squirrel-cage motors (asynchronous three-phase motors) have high starting currents. In order to prevent disruptive voltage fluctuations, power supply companies prescribe certain starting methods for high power motors. For motor powers above 4 kW certain starting procedures are necessary for three-phase motors.

Star delta starting

When starting using a star delta circuit the starting current and starting torque of three-phase motors are reduced to a third of the value for delta operation. This is the most common starting method. (It is less well suited in the event of a high load moment of inertia and small motor moment of inertia due to a marked speed reduction in the switchover pause).

Soft starting

It is possible to soft start three-phase asynchronous motors using fully electronic soft start devices. In this process the start-up current, and thus the start-up torque, is deliberately influenced by the voltage dosing (phase angle control).

We can differentiate between:

- Soft starters with adjustable run-up period (current limiting only possible by increasing the run-up period)
- Soft starters with adjustable maximum start-up current (the start-up time is automatically adjusted via the moment balance between motor moment and load moment).
- Soft starters with combined adjustment of run-up period and max. start-up current.

2.2 Control Functions

A measured-value transmitter installed in the system supplies the momentary actual value to the controller. This continually compares actual value and set value and progressively corrects any deviations. The control function is only ensured if the proper direction of control action is set for the controller.

When selecting a controller, it should be noted that the direction of control action can be selected. We can differentiate between two options:

Direction of control action for the controller:

1. Positive
If the set value is exceeded the speed falls (e.g. in pressure control)

2. Negative
If the set value is exceeded the speed rises (e.g. in inlet-side level control)

Controlled Quantity [Set Value]

- Pressure [bar]
- Differential pressure [bar]
- Flow rate [m3/h]
- Level [m]
- Differential pressure controlled by external temperature [bar]
- Differential pressure controlled by flow rate [bar]
- Differential pressure controlled by internal flow rate function (only possible for a single duty pump) [bar]
- Temperature [°C]
- Differential temperature [K]
- Temperature, combined with differential pressure [°C]
- Differential temperature, combined with differential pressure [K]
- Pure open-loop control mode, signal from external controller (external peak load)

Selection of controlled quantity

The objective of the following considerations is to find a controlled quantity that permits the pump to be adapted to system requirements by changing the speed.

The fluctuating system demand represents the main interference factor. The task of the control system is to cover the system demand despite these interference quantities and to largely eliminate the negative effects of the interference quantities, e.g. undesired pressure increases.

To this end the measurement location of the controlled quantity should be located as near as possible to the place where the interference arises (e.g. representative consumer installation). This ideal case is in practice hindered by the following problems:

a) Large distances between control system and ideal (representative) measurement point.

b) Branched systems with alternating or not very pronounced points of lowest pressure reading (representative consumer installations).

These problems too can be solved by proven optimization functions (see Optimization Functions)

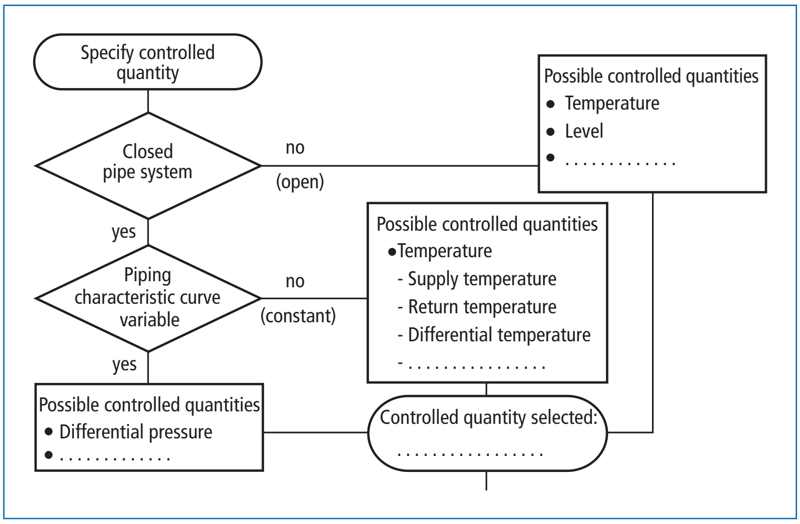


Fig. 71

The two most important decision-making criteria for the selection of the controlled quantity are based on the following questions:

1. Is the piping system a closed circulation loop or an open flow?

2. Is the piping characteristic curve variable or constant, i.e. does the system function at a constant or variable flow rate?

Once these two questions have been answered, an important preliminary decision has already been made for the most favourable controlled quantity.

In open conveyance systems the most common controlled quantities are
- pressure
- level
- flow rate

In closed circulatory systems these are
- differential pressure
- temperature

The controlled quantities are described in detail in what follows.

Set Value / Set Value Switching

In systems that do not impose any great requirements on the controlled quantities, fixed value control with a fixed set value is often used. However, since even in such simple systems the load behaviour can change greatly, set value switching between two basic set values permits a simple adaptation to the system load.

Criteria for switching can be:

– Manual pre-selection

– Signal from the process (limit value detector)

– Time-dependent

Optimization of the Controlled-operation Curve by:

- Internal variable (only possible for a single duty pump) in a
  - linear relationship
  - quadratic relationship
- External input in a
  - linear relationship
  - quadratic relationship (DPC curve; flow rate dependent set value readjustment); flow rate transmitter required

The objective of the optimization functions is to reduce the pump flow rate as far as possible, whilst still supplying all consumer installations sufficiently.

The duty limits of the pumps over the entire range of the characteristic diagram should be taken into account and – as far as possible – utilized.

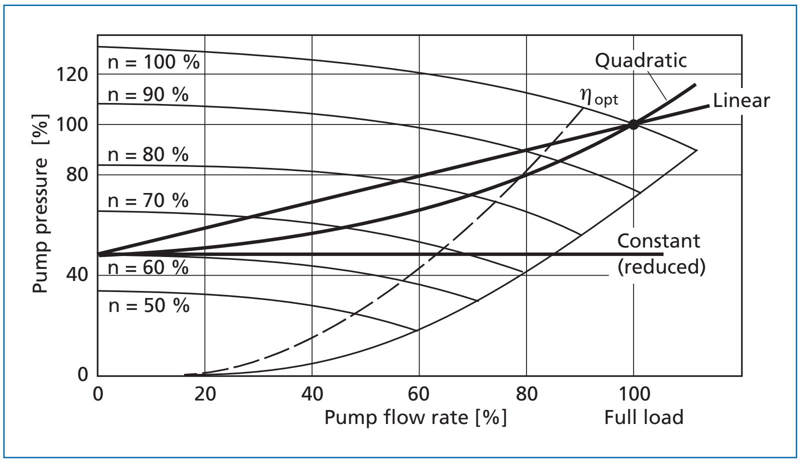


Fig. 72 One of the controlled-operation curves shown can be used depending upon load behaviour.

Control using set value readjustment:

In addition to the controlled quantity, further variables are taken from the controlled system that act upon the control input. This allows the controlled-operation curve to be easily adapted to the system requirements (the piping characteristic curve). Excess pressure, particularly in part load operation, and cases of inadequate pressure at full load, can be reliably avoided in this manner.

Parameter set switching

Switching to the 2nd Parameter Set

For further adaptation to the system requirements there is the option of switching over to a second controller (with separately adjustable parameters). It is thus possible to address changing system behaviour.

Monitoring the Pumps and the Hydraulic System in the Automatic Operating Mode

Even in the planning phase it is important to provide a suitable reliability concept for the entire system. The objective of this is to limit faults and, as far as possible, to maintain the function of the system. Impaired functional groups are switched off and, where available, replaced by stand-by groups or emergency functions. The most important monitoring functions for electric and hydraulic limit values are explained in what follows.

Excess current monitoring

Basic protective function for an electric motor against thermal overload in direct operation on the power supply system. Current-dependent protective devices that monitor the temperature of the motor winding indirectly by means of the current flowing in the supply line. This generates a current-dependent picture of the heat buildup in the motor. Over-current relays (bimetal) with a protective and back-up fuse or an over-current trip in a motor protection switch are used. An over-current trip behind a frequency inverter (FI) remains inactive since the FI limits the output current to a value below the tripping current. Therefore, in the worst case a blocked motor is supplied at nominal current and overheats due to lack of cooling.

Thermistor type motor protection

Greatly increased protection is offered by temperature measurement in the motor to be protected.

PTC thermistor detectors fitted in the motor winding directly monitor the temperature of the motor winding. When the nominal response temperature of the PTC thermistor is reached its resistance increases sharply, and the motor is switched off. Individually, klixon or other temperature monitors based upon bimetallic technology are also used for motor protection. If continuous temperature measurement is also desired, PT 100 sensors can also be used.

Dry-running protection

To protect the pumps, monitoring takes place to establish whether sufficient pumping medium is present. This can be determined by various measuring procedures. If the value falls below the set limit value the system is completely shut down and the corresponding message provided. The system can be restarted manually or automatically, depending upon the safety requirements. In any case, the fault message should be saved for the operating personnel.

Flow monitoring

Flow monitors are used to protect the pumps against overheating due to zero delivery. Flow rates that fall below the limit value briefly are unproblematic for the pumps and are not taken into account (e.g. during running up and running down processes).

In accordance with the main goal of the reliability concept – maintaining the operation of the system where possible – different reaction modes can be selected depending upon requirements. The requirement to protect people takes precedence over all protective and emergency functions.

Measuring Equipment

Particular care should be taken in the selection of the measuring equipment (transmitters). The operating reliability of an automation system stands or falls by the fault-free functioning of the detecting element. If the system operator uses special detecting elements with a high level of success for certain conditions of use, then the same type of detectors should be planned for new systems to be constructed. If no own values based upon experience are available with regard to detectors, then the supplier of the automation system should also supply the required detectors. This allows the functional and warranty problems to be greatly reduced.

In general, the following factors should be taken into consideration in the selection and fitting of detecting elements:

- Nominal operating pressure,
- Permissible max. pressure,
- Temperature limits for the ambient temperature and the temperature of the fluid pumped,
- Auxiliary power supply either via remote supply (measurement line) or via a local grid-fed supply device,
- Electric signal transmission for normal applications,
- Type and maximum length of the measurement signal cable (number of cores, cross-section, protection type),
- Optical signal transmission for special conditions of use, e.g.: large distance (1 km), environment with severe EMC interference, explosion protection.

The fitting location should be selected such that

- turbulence,
- air pocket formation, and
- dirt

cannot impair the measurement.

Differential pressure (pressure)

Common measurement principles:

- Piezoresistive measurement bridge on crystal membrane
- Inductive distance measurement of a metal membrane

For detecting elements it must be ensured that the sum of the maximum measuring pressure and the static system pressure remains below the permissible maximum pressure.

For high fluid temperatures the pressure measuring cable should be sufficiently long to allow the fluid to cool off. The measurement connections shall be arranged such that no deposits can enter the measuring cable (e.g. laterally or at the top of the main pipe).

Measurement parameters: throughflow / flow rate

Common measurement principles:

- Magnetic inductive measurement transducers
- Ultrasonic measurement transducers

Note:

The electronics usually consist of two components, a transducer with a measurement head and an evaluation device.

Minimum flow velocities are necessary for these measurement principles. Therefore a continuous measurement right down to a flow of zero is not possible. Both the minimum and maximum flow rate are decisive in the selection of a flow rate transducer.

The nominal diameter of the transducers is often smaller than the pipe (lower costs, higher velocities). The fitting position should be selected such that there is no air pocket formation or turbulence in the measured section. For magnetic-inductive measurement transducers, a minimum conductivity of the pumped fluid is necessary. Conductive deposits in the measured section (e.g. magnetite in circulatory systems) can lead to measurement errors. The ultrasonic measurement principle is sensitive to contamination of the conveyed fluid by solids.

Flow monitors

Common measurement principles:

- Calorimetric
- Flow paddle

Note:

Flow monitoring devices are primarily used as limit signal transmitters for monitoring and control purposes (dry-running protection, minimum flow detection).

The simple flow paddle is more sensitive to contamination and pressure surges in the pumped fluid.

Level detectors

Common measurement principles:

- Capacitive
- Hydrostatic pressure

Note:

Level detectors that function capacitively require a pumped fluid with certain properties (high dielectric constant, possibly conductivity).

They react sensitively to deposits on the electrodes. In the event of high levels of contamination of the fluid, dynamic pressure measurement using the bubbler control process has proved itself well.

Temperature sensors:

Measurement Principle:

Temperature-dependent resistance change

Note:

Submersion sensors have relatively long response times (slow reaction to temperature changes).

The design should be based upon the planned insulation of the pipe (sensor length).

Documentation

The costs and level of complexity of the system are of decisive importance to the content and scope of the documentation. For smaller systems or manufacturer's standard systems, mass produced documentation is normally sufficient.

For customized systems or large projects a description is required. Particularly when planning large objects it is frequently necessary to draw up the documentation according to the planning stage and project progress.

In addition to manufacturers' delivery times, the principal's approval phases should also be taken into account in the overall scheduling.

Installation

- Assembly (electrical and mechanical) of the set up control cabinet modules takes place in-situ.
- The laying and routing of cables and lines for the power supply, motors, detectors and centralized instrumentation and control connections takes place on-site.

The assembly of all components into a functional system must be carefully planned due to the numerous interfaces. The following summary includes the most important electrical tasks.

Assembly (electrical and mechanical) of the set up control cabinet fields in-situ takes place:

Site-supplied	– by the bidder
	– see separate quotation

Electrical connection of:

	Type	Qty.	Cross-section
Power cable	......	......	......
Motor cable	......	......	......
Sensor cable	......	......	......

Connection of all cables at the control cabinet

- Power supply
  Quantity / terminals
- Motor cable
  Quantity / terminals
- Sensor cable
  Quantity / terminals
- ....

Connection of all cable connections to

- Motor Quantity / terminals ......
- Sensor Quantity / terminals ......
- ....

Cable laying takes place

– By the customer

– By the bidder

Supply and laying in customer's cable routes

- Power supply
- Motor supply lead
- Sensor cable

Supply and laying of electrical cables including connection and fastening materials

- See separate quotation

Commissioning

The initial commissioning includes commissioning and functional testing of the (electrically and hydraulically) properly installed system and the supply of the handover log.

The system must be prepared such that all load ranges and operating states can be tested.

Estimated time required:

....

- Costs in accordance with KSB's terms and conditions for installation
- Costs for this are included in the quotation price

Each additional commissioning period required due to circumstances for which KSB is not responsible will be subject to an additional charge in accordance with the attached KSB terms and conditions for installation.

Additional costs such as accommodation, daily travelling and allowances will be charged at cost.

Extended commissioning

Test operation, instruction and optimization

Test operation of all control cabinets including the activation of all interlocks and protective devices

This also includes the performance of the necessary acceptance tests and the instruction of the operator's operating personnel. The operator shall bear in mind that commissioning and test operation cannot occur directly after the end of fitting and that it is possible that not all functional tests can be performed sequentially.

The costs will be charged on the basis of time and expense in accordance with KSB's terms and conditions for installation.

Training of operating personnel

Complex systems or those with high availability requirements require well trained operating personnel. The following training points are important for a safe operation of the system:

Process interactions and procedures, system operation, reaction to fault, fault detection and rectification. This training always takes place after the commissioning and acceptance of the system.

3 Project Planning Examples

3.1 System Description

The system is a district heating network. It comprises 26 heat transfer stations with a differential pressure requirement of 18 m at the transfer points. The heat transfer stations are connected via heat exchangers. The primary side output is adjusted by atmospheric conditions via a throttle fitting. The district heating system is designed for a supply temperature of 130 °C with a return temperature of 80 °C. The planned new construction is based upon a maximum heat output of 47 MW. The flow rate of 861 m^3/h is calculated from the maximum values of heat output and temperature differential.

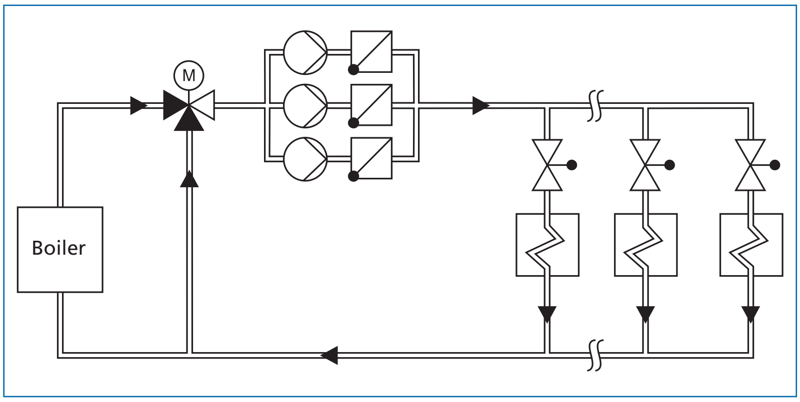


Fig. 73 System diagram

At this flow rate the piping system calculation results in a pressure loss of 24 m to the most remote heat transfer station.

Due to the differential pressure requirement of the heat transfer stations of H_w = 18 m and the maximum line losses of H_T = 24 m a pump head of $H_N = 42$ m must be met (provided).

3.2 Calculation of the Piping Characteristic Curve

(see also page 12 Fig. 14)

Once the nominal flow rate (Q_N) and line losses (H_T) have been determined the piping characteristic curve can be constructed.

$$H_x = H_T \cdot (Q_x / Q_N)^2$$
$$H_x = 100\ \% \cdot (Q_x / 861\ m^3/h)^2$$

Given Q_x [m³/h]	Sought H_x [m]
250	2
500	8.1
750	18.2
861	24

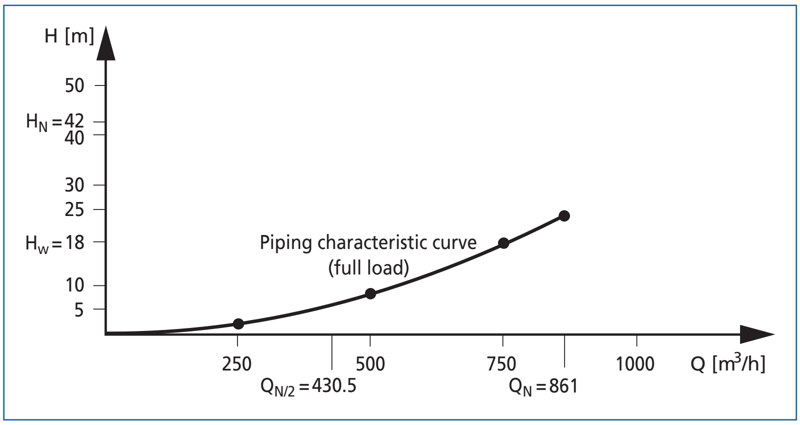
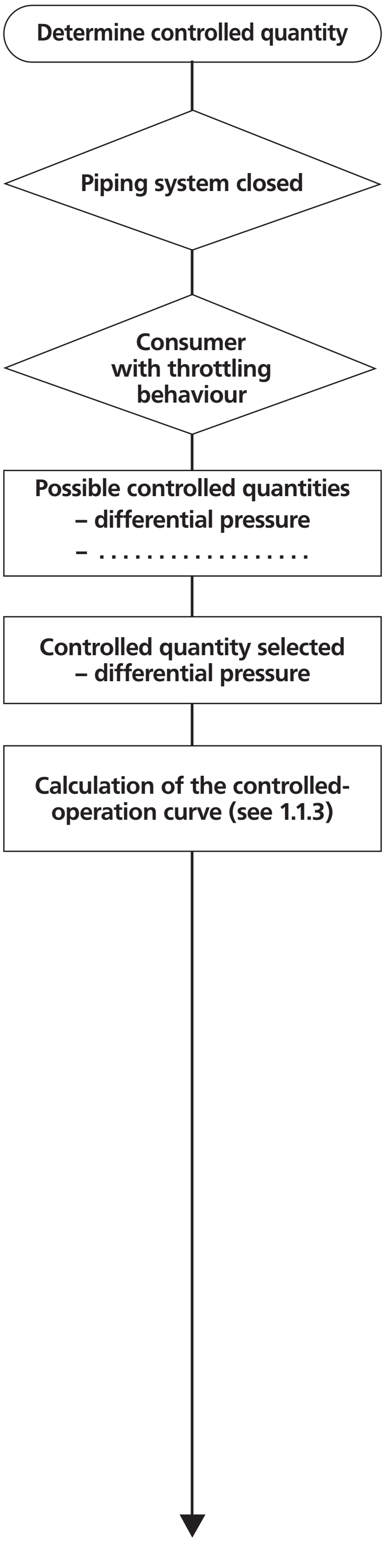


Fig. 74 Piping characteristic

3.3 Further Steps in Accordance With the “Project Planning Sequence Plan”

(please refer to page 71)



Detailed explanations on page 50

“Piping system closed”
Closed circulatory heating system

Output adjustment in heat transfer stations by means of external temperature controlled supply temperature in the consumer circuit

Since the consumer behaviour determines the system resistance, the differential pressure is the correct controlled quantity.

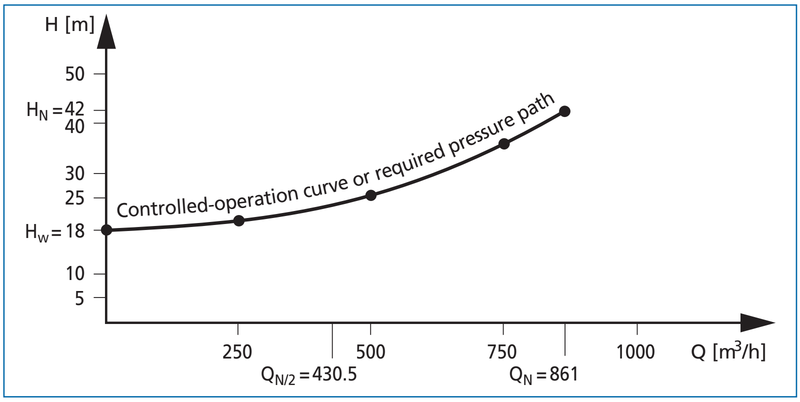
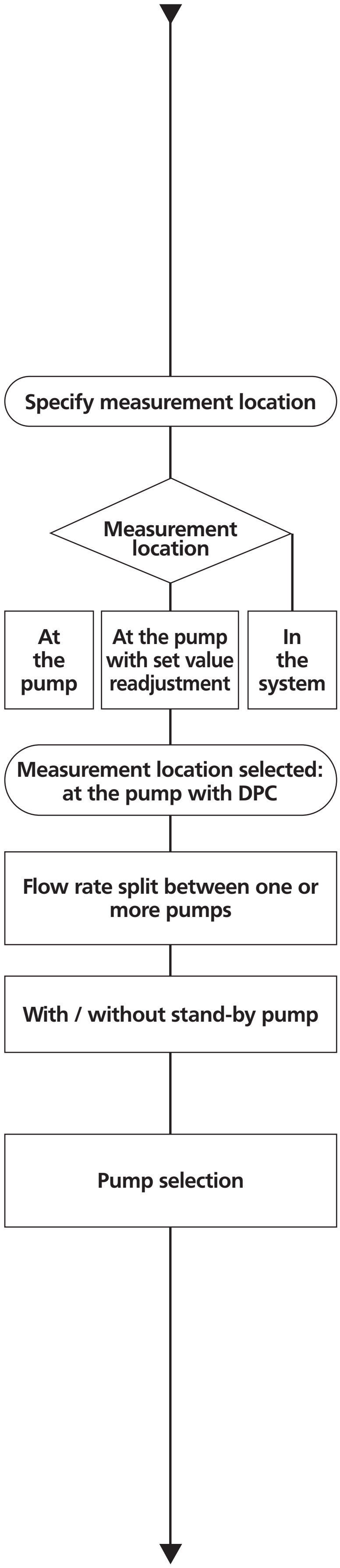


Fig. 75

$$H_x = (H_N - H_W) \cdot (Q_x / Q_N)^2 + H_W$$

$$H_x = (42\text{ m} - 18\text{ m}) \cdot (Q_x / 861\text{ m}^3/\text{h})^2 + 18\text{ m}$$

Given Q_x [m³/h]	Sought H_x [m]
0	18
250	20
500	26.1
750	36.2
861	42



The next step is to determine the required differential pressure curve.

To prevent undersupply at any of the heat transfer stations the minimum differential pressure must be 18 m. This means that even at minimum consumption ≅ 0 m^3/h this minimum pressure H_w ≅ 18 m must be maintained. As the flow rate increases the piping losses are added to this value (see also piping characteristic curve).

The origin of the parabola is moved to the level of the set value by a small expansion of the formula.

Due to the very extended system train a differential pressure measurement at the point of lowest pressure is not realizable (costs, worst point determination).

Since a flow rate measurement is available in any case (from energy metering), the differential pressure in the boiler house is also measured. The use of DPC, which is available in the modern KSB control systems (see page 40), provides a good alternative to measurement at the point of lowest pressure.

Due to the output data and the typical load behaviour (frequent operation at part load), the total flow rate should be split between two pumps.

For reliability reasons a third, equally sized pump is installed (pump power: 3 x 50 %). The stand-by pump is of course fully integrated into the automation concept (emergency changeover, alternating pump operation).

Full load point (new system design)

The nominal flow rate is divided between two identical pumps. For this nominal flow rate (Q_N) (see Fig. 76) a nominal head (H_N) is required. For the individual pumps (P_1), this means that at half the nominal flow rate ($1/2 \cdot Q_N$) they must still achieve the nominal head (H_N).

Part load operation

In part load operation care should be taken to ensure that the respective operating points of the variable speed base load pump lie on the so-called controlled-operation curve. The controlled-operation curve is specified such that at least the specified pressure is achieved. For reliable operation of the pump it is important that the given pump characteristic curve (at nominal speed) cuts the controlled-operation curve. In the example, this would be the point $B_{1,max}$.

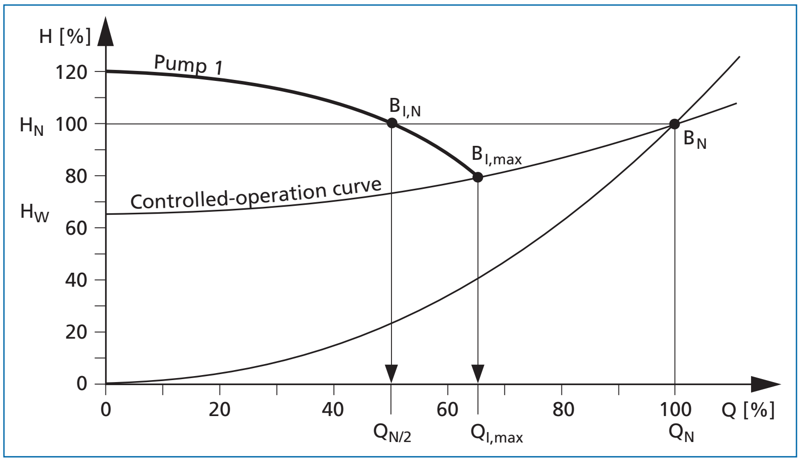


Fig. 76 H/Q diagram, schematic representation

Determine shaft power

From the relationships described for part load operation it is clear that the individually operated base-load pump requires its maximum shaft power (Pw, max) at the point B1, max. This value can be read off the pump diagram in question or calculated using the power formula.

Caution! The maximum shaft power of the base-load pump is greater than is the case for Q_{N2}.

Specify required motor power

The shaft power of the motor to be selected must be at least as great as the max. shaft power of the pump ($P_{w,\,max}$) plus safety factors. The safety factors take into account tolerances in the characteristic curves plus additional losses in the motor due to the frequency inverter. A 5 % safety factor is used in these calculations. Different safety factors are recommended depending upon the frequency inverter type and size.

For our example:

From the power diagram:	$P_{w,\,max}$	=	78.2 kW
Power safety factor	5%	=	3.9 kW
Required motor power:	P_2	=	82.1 kW
Next possible standardized motor size		**=**	**90 kW**

In Fig. 77 all important results of the project planning are brought together. At this point the hydraulic selection of the pumps and the specification of the operating behaviour in variable speed operation is concluded.

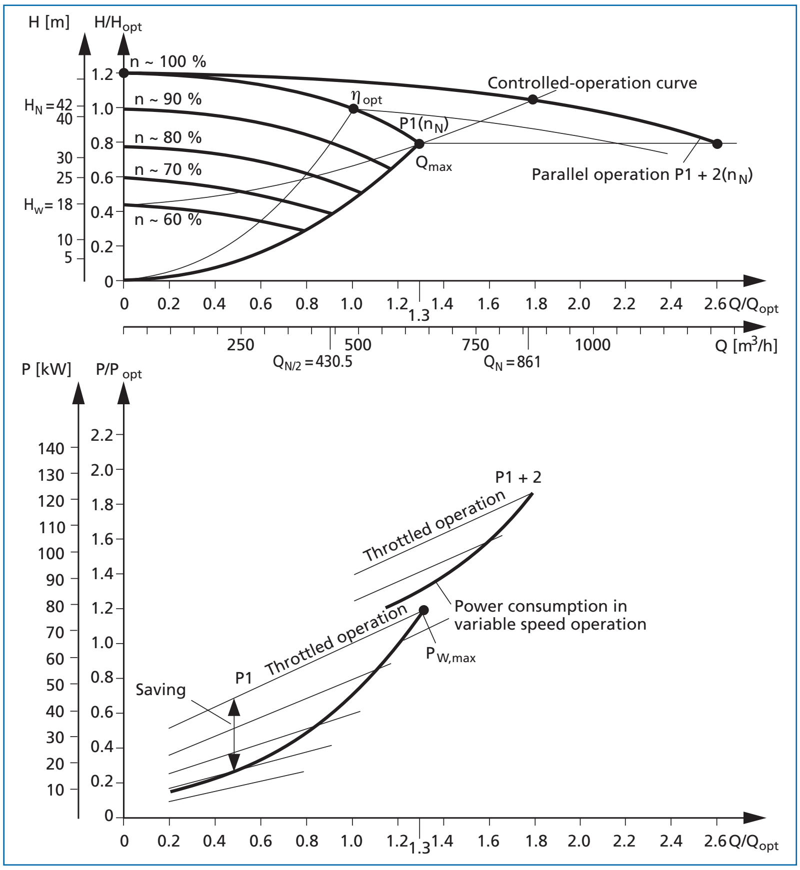


Fig. 77 H/Q diagram and power characteristic curve

Special requirements

A range of further conditions and requirements remain to be taken into consideration in the complete project plan. These are listed in the tender text for the system components.

For the pumps:
- Fluid type
- Materials
- Temperature
- Pressure, etc.

For the control system:
- Electrical equipment features
- Mechanical design, etc.
- Control technology interface

Special system requirements:
- Necessary safety precautions
  - Emergency stops
  - Overpressure protection devices
  - Emergency power supply, etc.
- Process conditions
  - Starting process according to time program
  - Control quality (tolerances)
  - Manual intervention option, etc.

System description
Tender texts

Automatic pump control brings a technical system into the required operating state (e.g. demand-dependent). The system should monitor itself, avoid critical operating states and put itself into a safe state in the event of faults.

The general method of functioning and the interaction of the individual components and assemblies are represented in the system description.

The tender text specifies the required system, operation and power data. In addition, the tender text includes a precise technical specification of the devices and components used and, where applicable, the desired commercial conditions.

Economy calculation

For economy considerations, the electrical power requirement of two fixed speed pumps is compared with the power requirement in variable speed operation. The latter system operates with a variable speed pump and a fixed speed peak load pump. The district heating system that underlies this example has consumer installations with throttling characteristics.

A comprehensive description of an economy calculation study is included in the fundamentals section (Chapter 1.1.4). Furthermore, the calculation of the pump characteristic curves for operation with speed adjustment is also described in this section.

Procedure:

The power consumption characteristic curves in controlled operation are determined graphically using the H/Q diagram and the given controlled-operation curve (Fig. 80).

For our practical example the following permissible simplifications are made:

- The saved shaft power P_w is set equal to the saved electric effective power
- The various switching limits for the peak load pump in fixed and variable speed operation are not taken into consideration
- Using the load profile, certain load states are assigned annual operating times and in the power diagram the associated power consumption savings.

  A standardized load profile can be found in the approval specifications for the German environmental “Blauer Engel” label for heating circulators (RAL-UZ105)

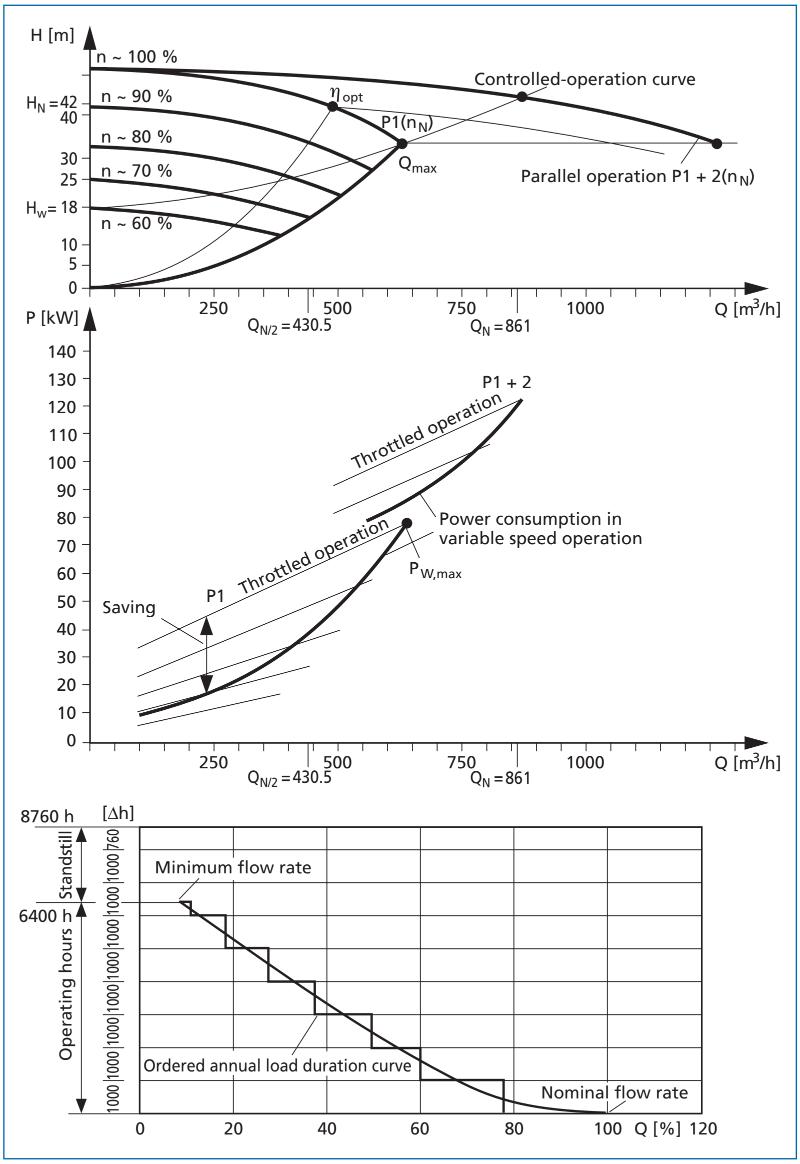


Fig. 78 Characteristic curves for the economy calculation

The results are summarized in the economy calculation table (see below). The following influencing factors are relevant to the calculation of payback periods:

- New system/old system (modernization)
- Competence of the switchgear
- Company-specific calculation methods
- Price of electricity inc. additional costs

Depending upon the influencing factors a payback period between 1.8 and 2.9 years should be expected.

Result:

Under the assumed conditions, annual electricity cost savings of approx. € 14,500 can be expected for the circulating pumps.

Depending upon the influencing factors a payback period between 1.8 and 2.9 years can be expected.

Economy calculation

ΔP_E kW	B h/a	S Euro/kWh	ΔE_E Euro/a
19	1000	0.10	1,900.--
15	1000	0.10	1,500.--
21	1000	0.10	2,100.--
26	1000	0.10	2,600.--
26	1000	0.10	2,600.--
28	1000	0.10	2,800.--
25.5	400	0.10	1,020.--
			Σ 14,520.--

Key:
ΔP_E : Saved electrical power
B : Operating hours
h/a : Hours per year
S : Electricity costs
ΔE_E : Saving on electricity costs
$\Delta E_E = \Delta P_E \cdot B \cdot S$

4
Reasons for Pump Automation and Control

4.1
Operational Reliability

a) Protective measures	e.g. • Pump changeover for equal distribution of pump operating hours • Ensuring minimum pump flow rate • Monitoring of pump characteristic diagram to avoid impermissible operating states	**Benefits:** • **Higher system availability**
b) Fault changeovers	e.g. • Changeover to – stand-by pump – stand-by frequency inverter – mains operation	**Benefits:** • **The pumping task continues to be fulfilled**
c) Monitoring	e.g. • Limit values for – lack of water – temperature – controlled quantity • Switching off the system	**Benefits:** • **Protecting the system against severe damage**

4.2
Improving Operating Behaviour

a) Holding process data constant	e.g. • Differential pressure in district heating systems • Pressure in pressure boosting systems • Level in sewage works • Flow rate in water treatment	**Benefits:** • **Process optimization ensures uniformly high quality**
b) Reducing pressure surges	e.g. • In water supply systems	**Benefits:** • **Higher operating reliability** • **Reduction of shocks, noises and material destruction**
c) Reduced switching frequency	e.g. • In water supply systems	**Benefits:** • **No “fluttering”**
d) Reduced flow noise	e.g. • In heating element thermostatic valves	**Benefits:** • **Greater comfort**

4.3 Increasing Product Quality

a) In machine tools	e.g.	• Constant pressures in cooling lubricant systems • Lower transfer of heat from the pump into the cooling lubricant	Benefits: • More accurately dimensioned workpieces
b) Mill trains	e.g.	• Adapted flow rates and pressures at the nozzles	Benefits: • Higher quality steel profiles

4.4 Reducing Operating Cost / Life-Cycle Cost

a) Effective requirement optimization	e.g.	• Adaptation of the pump output to the requirement profile of the system	Benefits: • Reduced investment cost • Saving in electricity costs
b) Reduced drive power costs	for	• Over-dimensioned pump output • Systems with mainly low-consumption operating times • High motor power	Benefits: • Saving in electricity costs
c) Protection of system components	e.g.	• At throttling elements, pipelines and pumps	Benefits: • Saving in maintenance costs
d) Reduced energy loss of the system	e.g.	• In district heating the overflow valve seldom trips in, therefore less heat is lost into the earth	Benefits: • Saving in fuel costs
e) Modified flow rates	for	• Water shortage by reduction of the set value characteristic curve	Benefits: • Protection of water reserves

4.5 Improving System Information

a) Pump operating data	e.g.	• Capture • Summarization • Assignment • Evaluation • Display	Benefits: • Determining weak points • Information on operating sequences • Optimization of the system • New findings that feed into planning of new systems
b) Process information	e.g.	• Evaluation of sensors • Storing of measured values, fault data, etc. • Operating statistics • Fault detection and diagnosis • Trend recognition	Benefits: • Reduction of the inspection and servicing cost • Early detection of damage
c) Data transmission via bus system	e.g.	• Start / stop • Set value / actual value • Fault • Status	Benefits: • More information • Simpler transmission • Simpler processing

5 An Overview of Automation Concepts

Depending upon the pumping task requirement and the operating conditions to be observed, various electrical and hydraulic circuit concepts may be the most favourable solution. These range from one variable speed pump to several equally or differently sized pumps with one or more frequency inverters. Hydraulically, the options range from pumps connected in parallel through pumps connected in series to a combination of both.

Figs. 79 and 80 show an overview of the most common circuit options. Some parallel configurations are briefly described on the following pages.

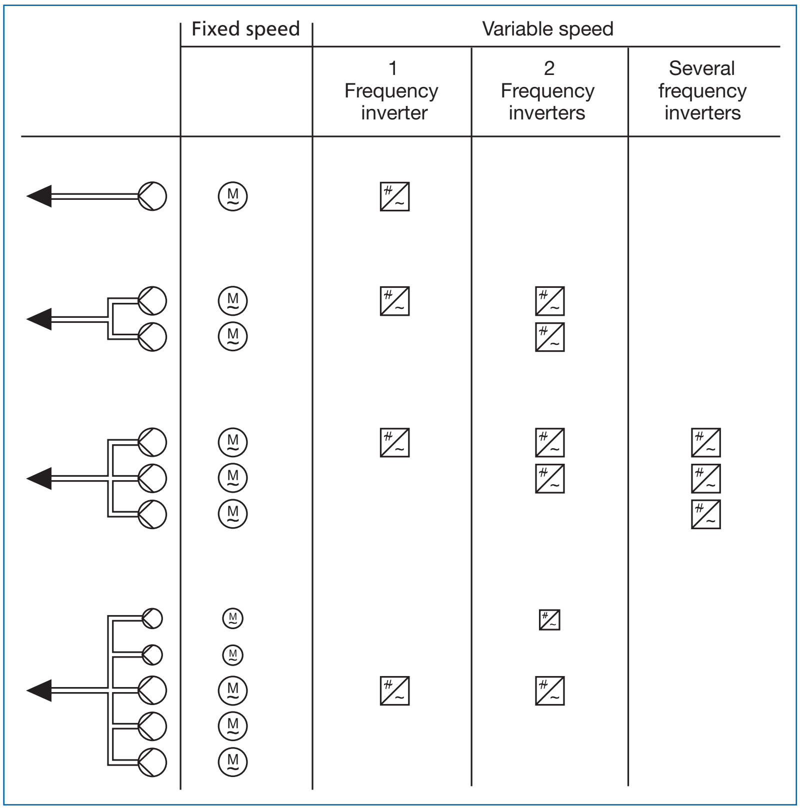


Fig. 79 System diagram "Parallel connection of centrifugal pumps"

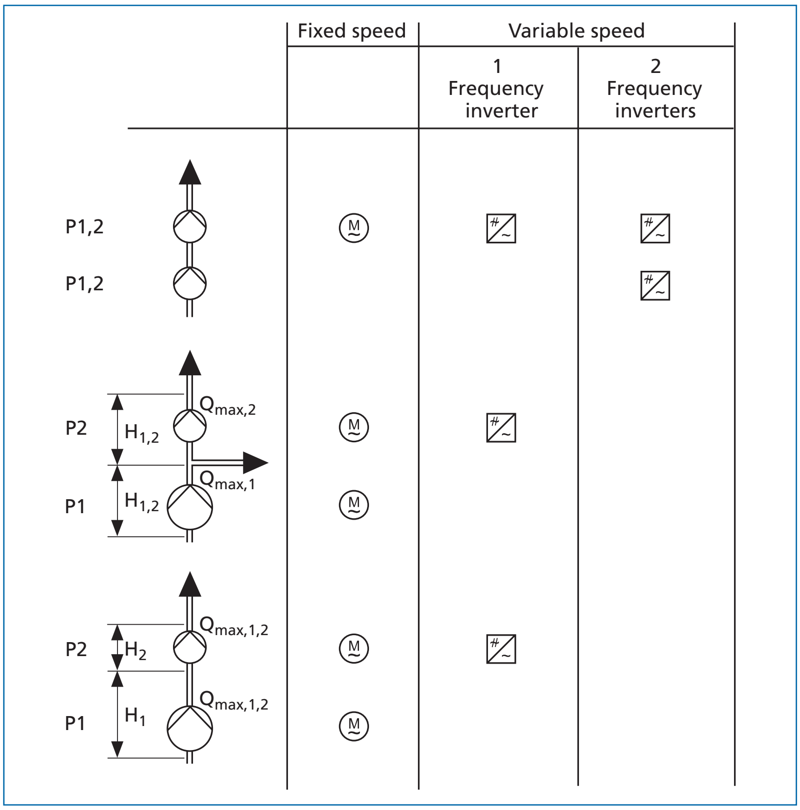


Fig. 80 System diagram "Series connection of centrifugal pumps"

5.1 Parallel Connection of Identical Pumps with One Frequency Inverter

(one pump in variable speed operation on an alternate basis)

The flow rate is split between several equally sized pumps, resulting in:

- Good adaptation to demand
- Simple layout with regard to
  - electrical system
  - control technology
  - hydraulic system

Each pump unit can be operated both through a frequency inverter and on the 50 Hz grid. This results in:

- Operating reliability
- Equal distribution of operating hours by alternating the pumps in variable speed operation
- Fixed speed peak load pumps provide a cost-effective increase of the flow rate
- Steady controlled-operation curve even in parallel operation with fixed speed pumps, since the pump system pressure is determined by the variable speed pump

If the pump output is reduced – by reducing the speed – only a greatly reduced shaft power is required. This effect is also achieved after peak load pumps have cut in.

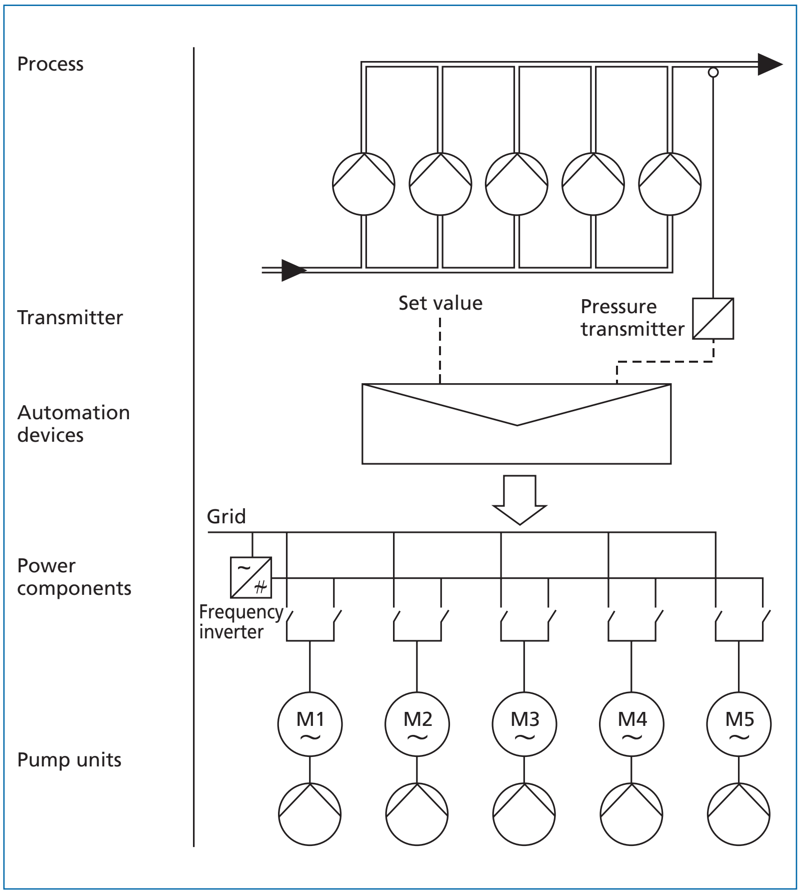


Fig. 81 "Parallel connection of centrifugal pumps"

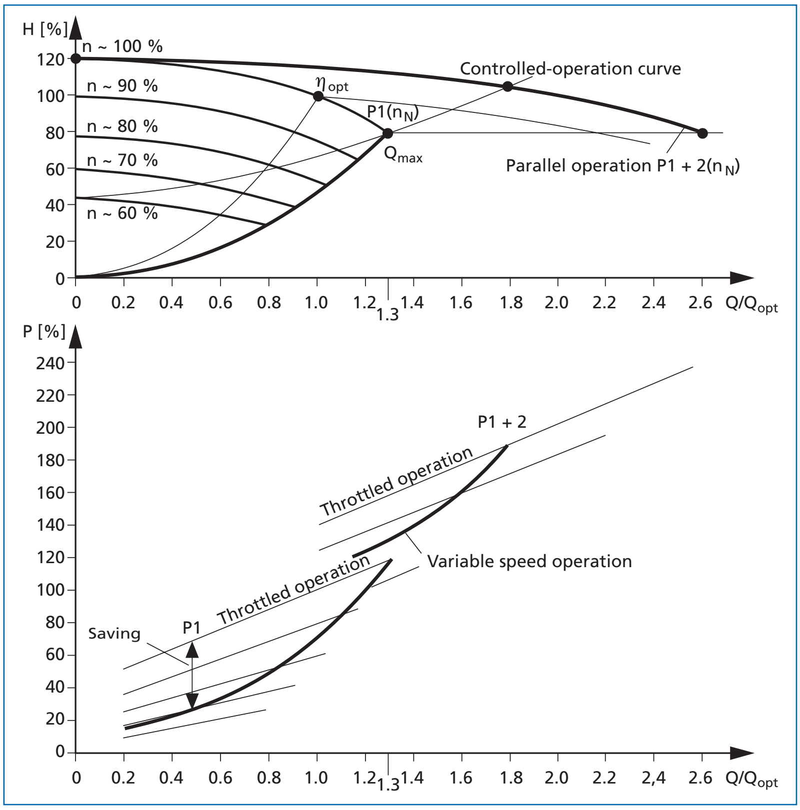


Fig. 82 Power diagram for the "parallel connection of centrifugal pumps"

5.2 Parallel Connection of Identical Pumps with Two Frequency Inverters

(2 pumps in variable speed operation on an alternate basis)

The flow rate is split between several equally sized pumps. Each pump unit can be operated on each of the two frequency inverters and on the 50 Hz grid.

This results in:

- High operating reliability
- Starting current of the variable speed pumps limited to nominal current.
- Electrically and hydraulically soft pump changeover possible.

Due to the option of operating two pumps by means of two frequency inverters, the following main hydraulic advantages are obtained:

- Greatly increased adjustment range
- The pump limit curve Q_{max} P1 is doubled to Q_{max} P1+P2
- Soft hydraulic running up and running down of the variable speed pumps and greatly damped operating behaviour of the fixed speed pumps.

Further savings are possible compared to operation with just one frequency inverter. The main reasons for this are:

- Greater adjustment range, e.g. greater utilization of inlet pressures
- Better part load efficiency with more than two operating pumps.

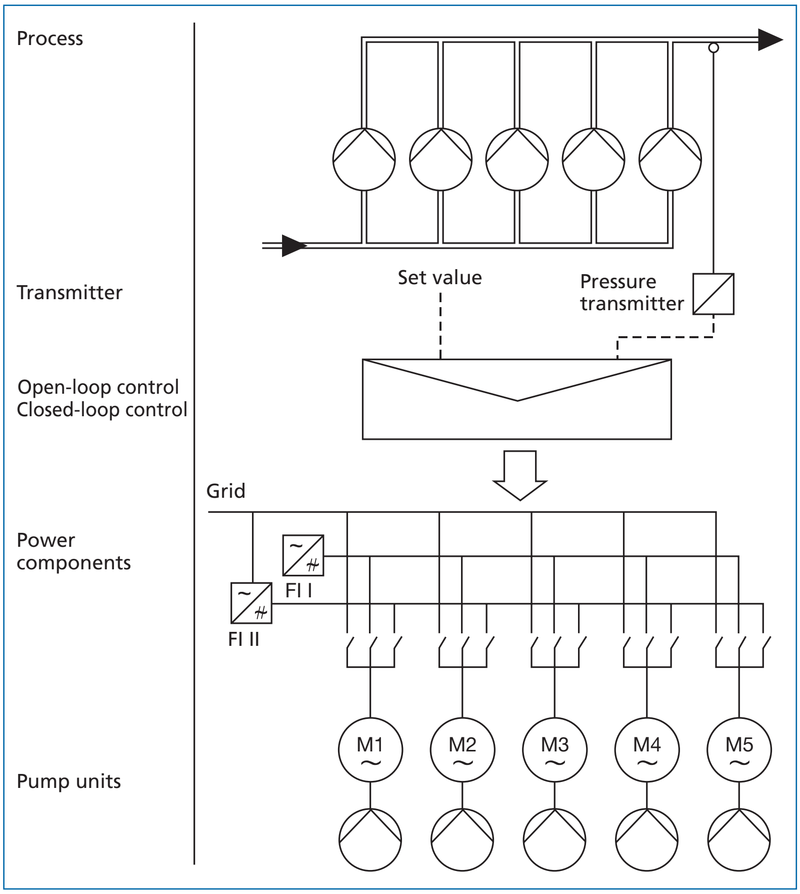


Fig. 83 System diagram "Parallel connection of centrifugal pumps"

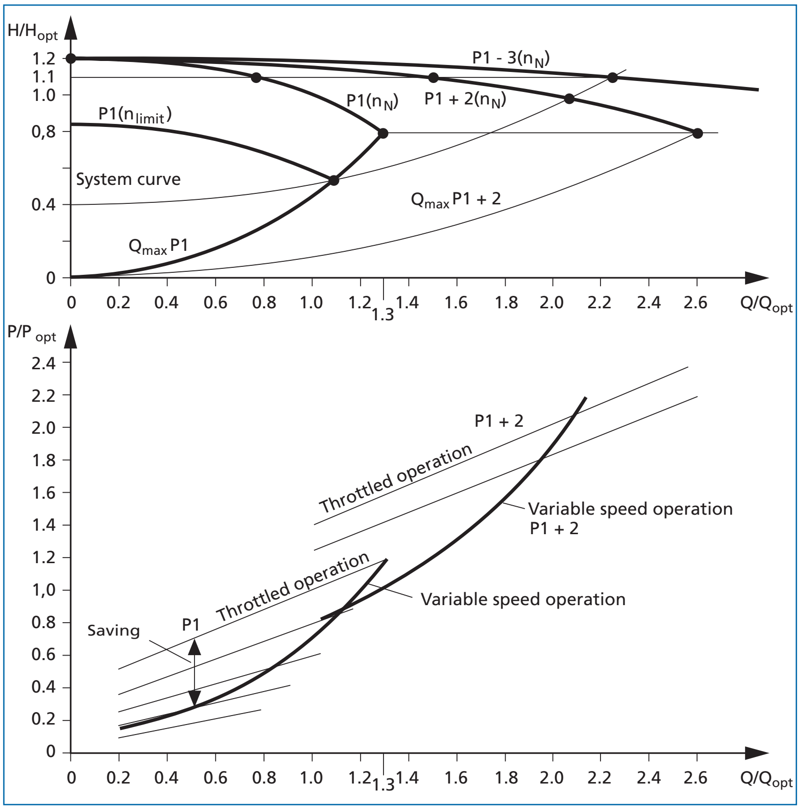


Fig. 84 Power diagram for the "parallel connection of centrifugal pumps"

5.3 Parallel Connection of Non-Identical Pumps

(of 3 main pumps and one or two base-load pumps; one pump of each group with variable speed option)

The total flow rate is divided between a low-load pump and several main load pumps. Such systems are usually used in installations with sharply fluctuating consumption. This applies both to systems with consumption fluctuations based upon the time of year, for example, and also to systems with frequent consumption changes in a daily work cycle.

The system can be designed such that an identical stand-by pump is available for the low-load pump. For moderate reliability requirements, this pump can be dispensed with. The supply is then taken over by the main pumps in emergencies.

The low-load range is covered by a small pump. As a result, the following should be achieved:

- Better pump efficiency
- Minimum flow rate to the main pumps ensured
- Reduction in switching frequency at low load

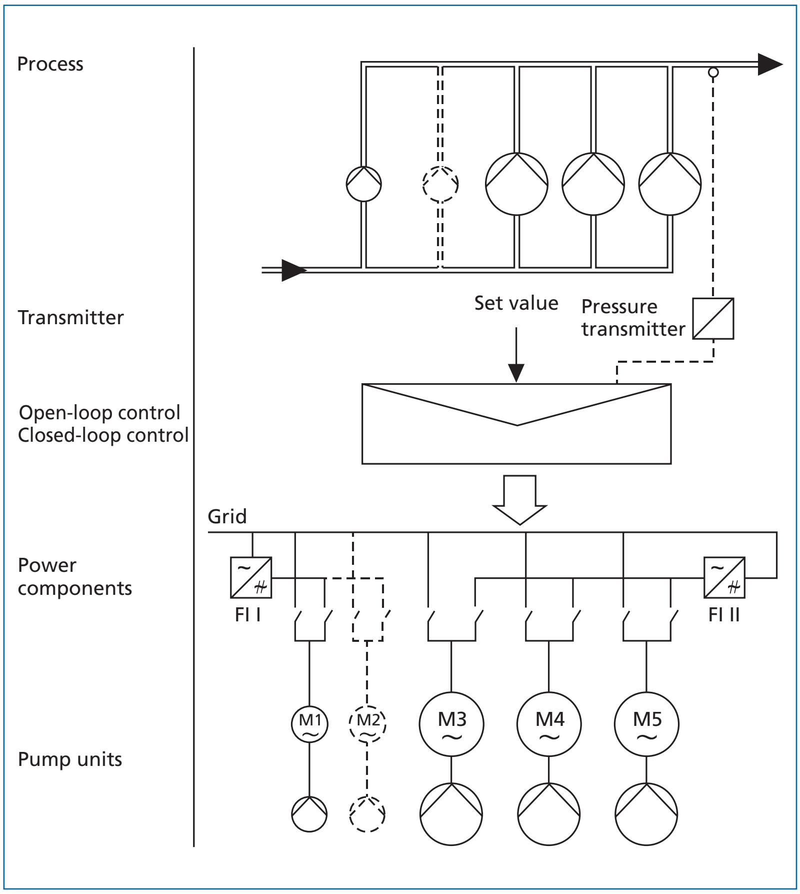


Fig. 85 System diagram "parallel connection of centrifugal pumps"

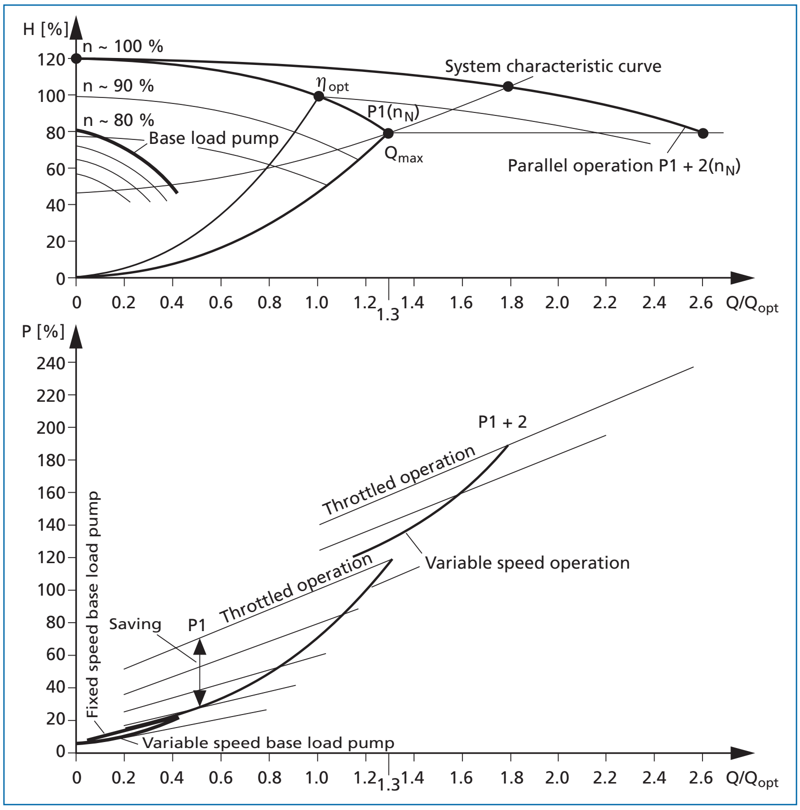


Fig. 86 Power diagram for the "parallel connection of centrifugal pumps"

5.4 Further Electric Configuration Concepts from the KSB Product Range

The optimal solution, from a control point of view, is one in which each pump/motor is assigned a frequency inverter. The disadvantage of this is the higher equipment costs and a greater space requirement. For certain applications (e.g. district heating with two supply and return pumps each) this is the best solution.

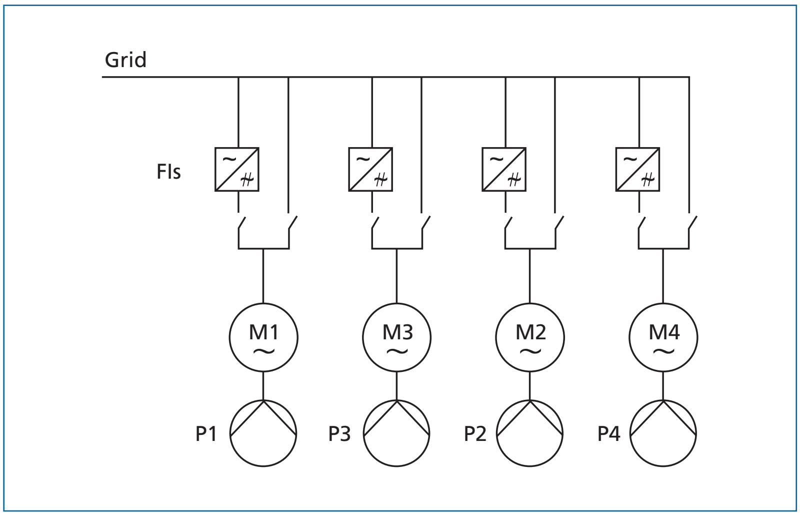
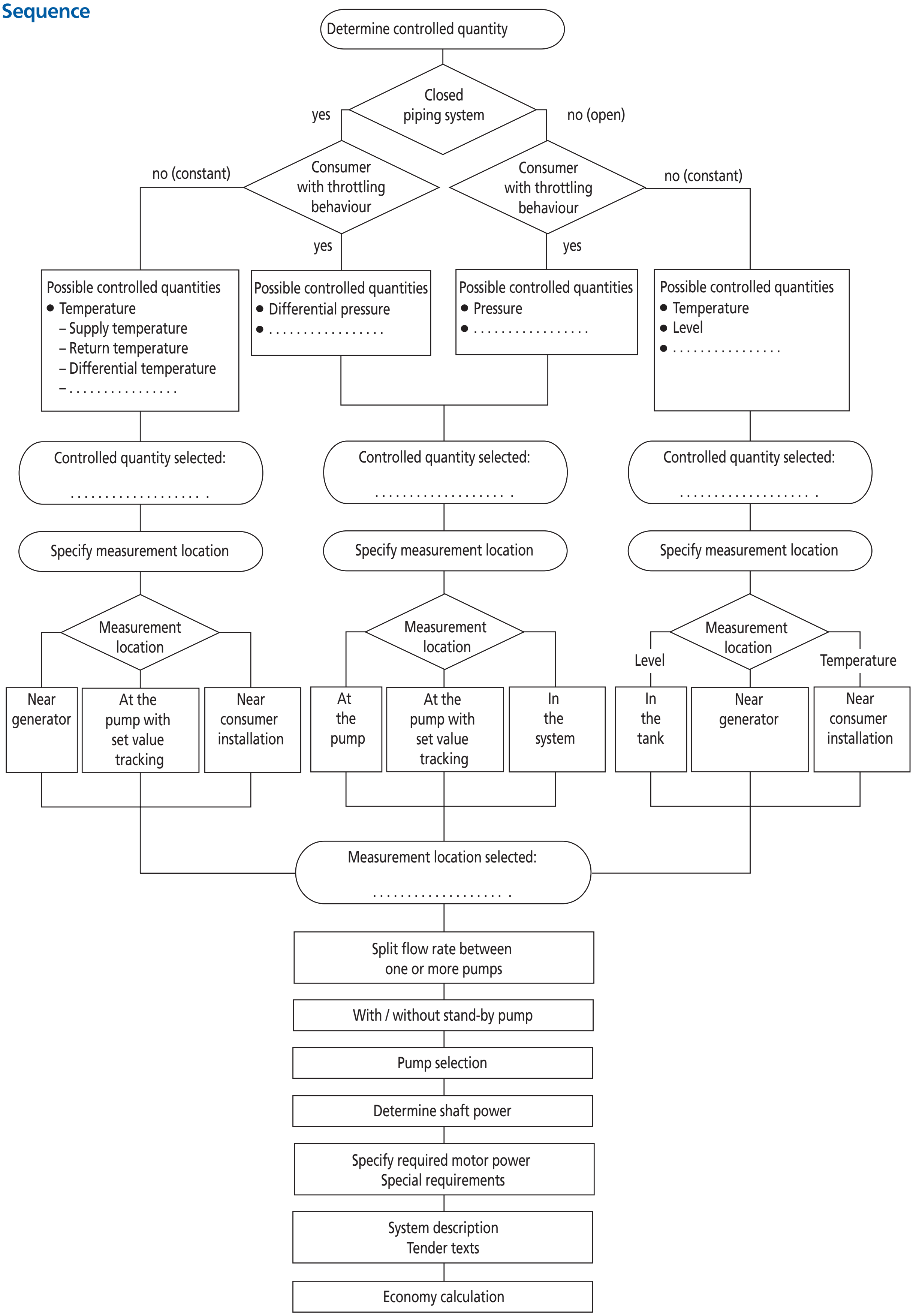


Fig. 87 Each pump is assigned a frequency inverter

Overview of Project Planning Sequence



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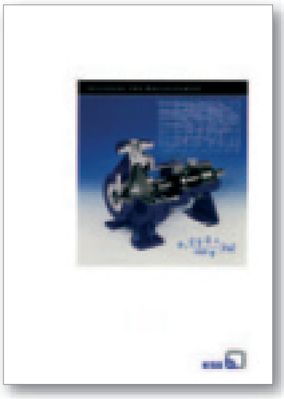

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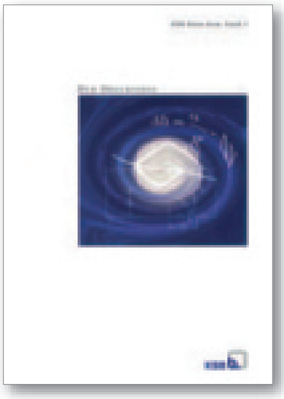

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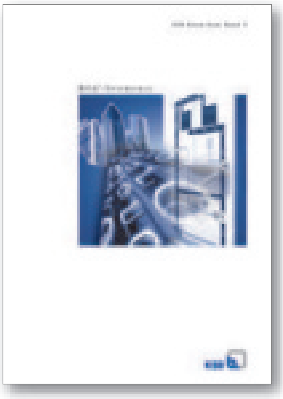

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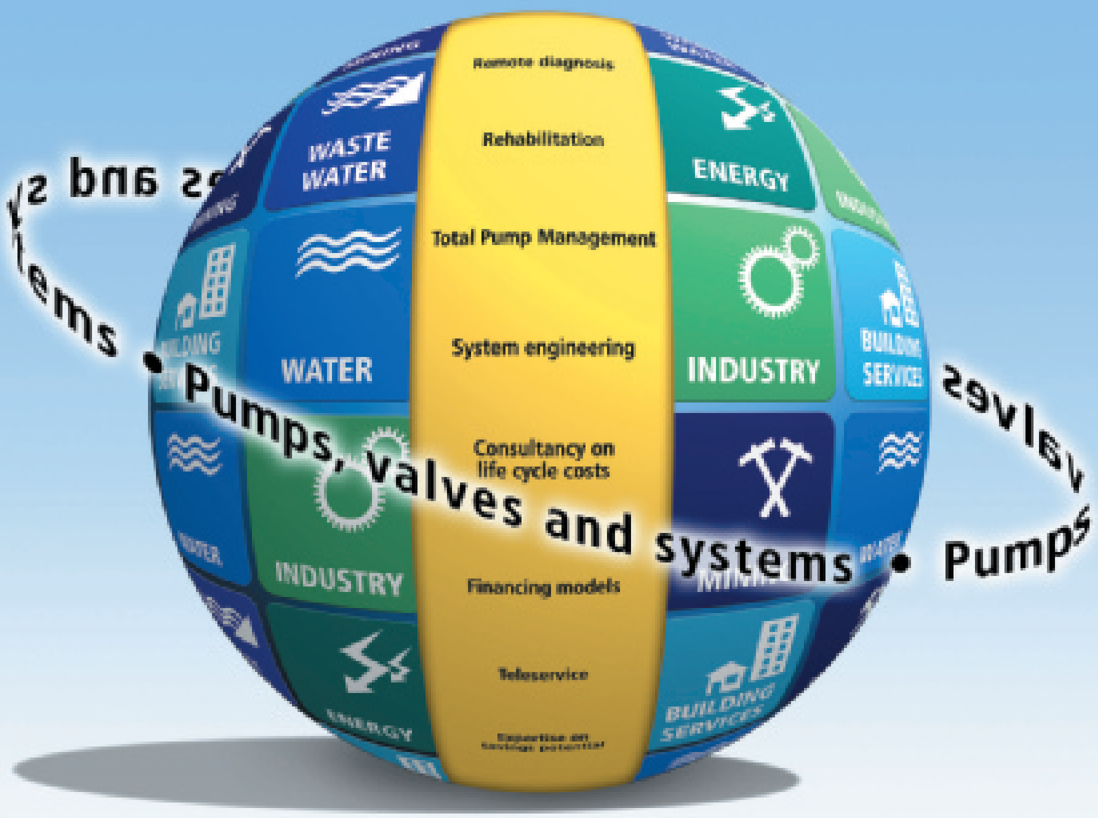

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