Mads Mysen • Peter G. Schild • Axel Cablé

SINTEF
RESEARCH
24

Demand-controlled ventilation – requirements and commissioning

GUIDEBOOK ON WELL-FUNCTIONING AND ENERGY-OPTIMAL DCV

SINTEF

SINTEF Research

Mads Mysen, Peter G. Schild and Axel Cablé

Demand-controlled ventilation – requirements and commissioning

Guidebook on well-functioning and energy-optimal DCV

SINTEF Academic Press

SINTEF Research 24
Mads Mysen, Peter G. Schild and Axel Cablé
Demand-controlled ventilation – requirements and commissioning
Guidebook on well-functioning and energy-optimal DCV

Keywords in English:
energy use, demand-controlled ventilation, specific fan power

Norwegian title:
Behovsstyrt ventilasjon (DCV) – krav og overlevering
Veileder for et energioptimalt og velfungerende anlegg

Keywords in Norwegian:
energibruk, behovsstyring, ventilasjon, SFP

Project number: 102000025
ISSN 1894-1583
ISBN 978-82-536-1414-4 (pdf)

Cover illustration: SINTEF Media

SINTEF Academic Press
Address: SINTEF Building and Infrastructure
Forskningsveien 3 B
PO Box 124 Blindern
N-0314 OSLO
Tel.: + 47 22 96 55 55
Fax: 22 96 55 08

www.sintef.no/byggforsk
www.sintefbok.no

Preface

In order to reach the targets set by the stricter energy building regulations, it is necessary to set up strategies to drastically reduce the energy use of buildings. Priority should be given to measures that provide the largest energy-saving potential at the lowest cost. Reducing the ventilation rate with Demand-Controlled Ventilation (DCV), and hence reducing both fan power and heating/cooling demand, are the measures which constitute the largest and most profitable potential of energy saving in new and existing educational and office buildings (Smiths, et al., 2013). Other measures, such as increasing insulation, appear to be much less cost efficient. This means that energy-optimal DCV is crucial in order to satisfy the newer energy requirements in educational and office buildings.

Most of the content of this guidebook results from the Norwegian research and development project «reDuCeVentilation – *Reduced energy use in Educational buildings with robust Demand Controlled Ventilation*». The purpose of reDuCeVentilation was to develop solutions to provide a good indoor climate with minimal energy use in educational buildings. The presented solutions are also suitable for office buildings.

The purpose of this guidebook is to help building owners to acquire well-functioning demand-controlled ventilation by applying the recommendations given in Chapter 2, and proper commissioning (balancing and load-test as described in Chapters 4 and 5). Contractors and property managers can use this guidebook to improve the quality of new systems, while facility managers can use the guidebook for troubleshooting and maintenance of existing ventilation systems (Chapter 6).

Each chapter begins with a short summary entitled *Recommendations in a nutshell*.

reDuCeVentilation was led by SINTEF Building and Infrastructure. It started in 2009 and finished in 2013. The project was supported by the Norwegian research council, VKE, Skanska, Undervisningbygg Oslo KF, Optosense, Micro Matic Norge, Swegon and TROX Auranor Norge who are gratefully acknowledged.

This guidebook, as well as other results from the project, can be downloaded on:

http://www.sintef.no/Projectweb/reduceventilation/

Contents

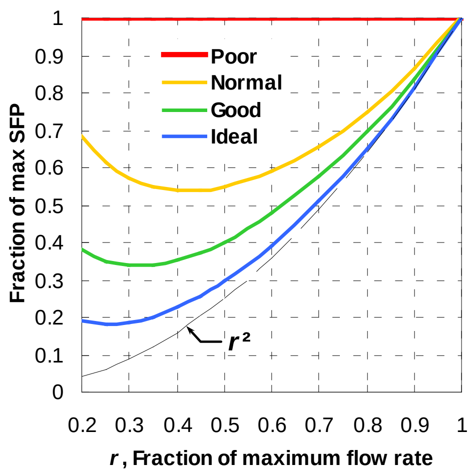
Abstract

DCV stands for Demand-Controlled Ventilation. That is to say, ventilation systems that automatically regulate the ventilation rate according to a demand measured at room-level. DCV systems must therefore have a sensor in the room, which gives a measure of the indoor air quality, and this signal is used to control the ventilation rate to achieve the desired indoor air quality. There are large differences between different DCV systems, both in terms of functionality and cost. There are also significant differences in performance between DCV systems and simpler systems which, for example, vary the airflow rate with preset air damper positions, or which use a single sensor for several rooms. In order to verify that a DCV system fulfills the expectations in terms of indoor climate and energy use, one must specify measureable objectives of performance. **Therefore, we recommend setting specific performance requirements for DCV. These are given in Chapter 2.**

It must be possible to control the specified requirements. The most important control points are presented on the figure below. All air handling units (AHU) should go through a functional check as part of commissioning. We recommend an automated load test with minimum and maximum supplied airflow rates to all the rooms, for maximal and reduced AHU airflow rate. If it is not possible to perform an automated load test, because of the chosen components and/or programming, we recommend checking all the rooms by measuring the ventilation rate for maximum and minimum fan speed, for maximum and reduced system load. This manual functional check should be documented with a completed VAV-control form.

Moreover, we recommend setting requirements to the following points:

1. Specific Fan Power (SFP) for maximal and reduced airflow rate
2. changes in airflow rate at room level should result in the same change in the total airflow rate through the AHU
3. documentation in the form of a functional description and a DCV system diagram (both electrical and duct system)
4. balancing and control of the airflow rates (completed VAV-control form)
5. accuracy, calibration specifications, and lifespan for the chosen sensors and DCV dampers
6. SFP shall be measured such that power losses in Variable Speed Drives are included, preferably using a suitable 3-phase energy analyzer, or by direct reading on the AHU



In addition, pressure-controlled systems shall be balanced in order to:

- verify that the location of the pressure sensor is suitable
- set the appropriate pressure set point
- adjust any fixed balancing dampers in relation to the motorized control dampers

Deviations during commissioning are normal and should be expected. Therefore, it is important to either forecast time to improve the system, or to create a model for economic compensation to take into account the deviations from the requirements which affect the energy consumption.
Furthermore, new discrepancies will occur during the operational phase of the building. It is essential that the automatic controls and the Building Management System (BMS) make it easy to detect faults. It is also important that the control components are accessible for inspection, service and replacement.

Part 1 Principles and requirements

1 Alternative DCV systems and sensors

Recommendations in a nutshell:
The type of demand-control strategy used should be specified! DCV stands for Demand-Controlled Ventilation, which means that the ventilation rate is controlled automatically, and in real-time, according to a demand measured at room-level. This implies that a DVC system must have room sensors which give a measure of the indoor air quality in each room. This signal is then used to control the ventilation rate according to the desired indoor air quality. It is necessary to specify quantitative objectives in order to obtain a system that fulfills the expectations. This chapter provides a quick introduction to various DCV systems.

1.1 Background

DCV systems are ventilation systems in which the air flow is controlled automatically according to a demand measured at room level (Maripuu, 2009). This means that DCV systems must have a sensor in each room giving a continuous measurement of the indoor air quality. This signal is then used to control the airflow rate according to the desired indoor air quality level.

VAV stands for Variable Air Volume. It is a broader term than DCV, as it encompasses all systems with variable airflow rate, irrespective of the type of control. The type of control can range from time-control of fan operation to advanced energy-optimal control of both fans and air dampers according to a demand measured at room-level by gas-sensors etc. There is a major difference between those two extreme cases both in terms of cost and functionality. It is therefore necessary to specify the exact type of control used, and to set quantitative objectives in order to obtain a ventilation system that fulfills these expectations. Only VAV systems which control the airflow rate according to a demand measured in the room, and not according to a preset value, are considered as DCV in this guidebook. These are designated as DCV systems with DCV components.

The different underlying principles for DCV are briefly described in this chapter.

1.2 Pressure-controlled DCV

Pressure-controlled DCV is the most common principle for DCV (Figure 1.1).

Motorized dampers control the airflow rate supplied to the rooms according to the demand measured in each room. A change in the ventilation demand causes a change in a damper's position, which influences the static pressure in the duct. The pressure sensor should be sensitive enough to record the change in static pressure. The pressure sensor is connected to a controller, which maintains a constant pressure at the location of the pressure sensor, by varying the speed of the fan.

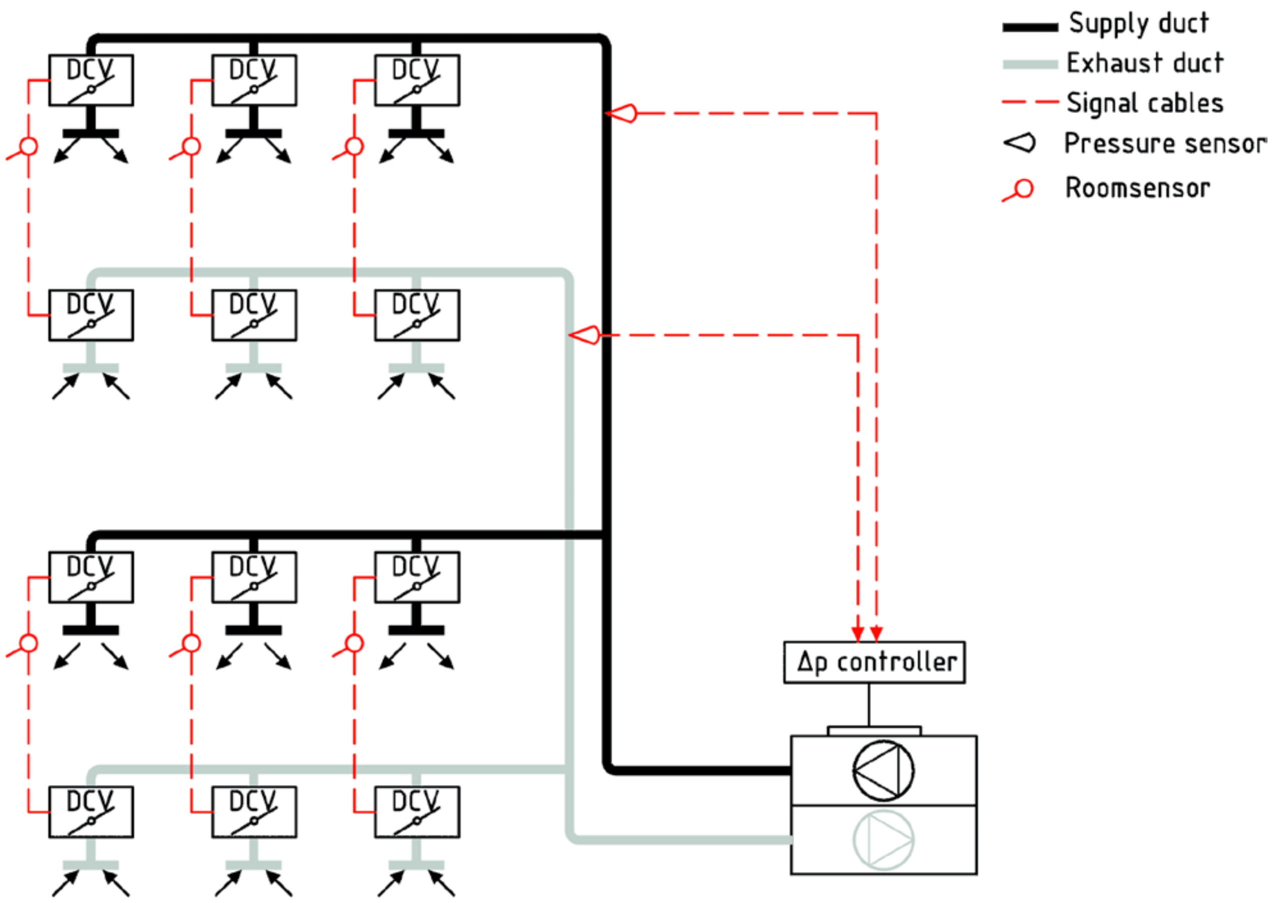


Figure 1.1 Illustration of DCV with constant pressure control. The fan speed is controlled so as to keep constant static pressure in the main ventilation duct, at the location of the pressure tap.

Controlling fan speed to maintain a constant static fan pressure rise results in unnecessary throttling during part-load conditions. Pressure-controlled DCV therefore requires more fan energy than the Static-Pressure-Reset DCV or Damper-Optimized DCV principles, which are both described below.

Energy-use is minimized by locating the pressure sensor as far from the fan as technically possible in terms of controllability. This minimizes the average fan pressure, and hence fan energy use. However, if the pressure sensor is located close to the fan, the fan pressure will be higher on average, resulting in a high fan energy use. Moreover, this location is not ideal in terms of control, because the pressure variations at room-level result in minor pressure variations at the location of the pressure sensor, which may not be sensitive enough to react to those variations. Consequently, the variations of the demand in a room may result in a variation in the distribution of air to the other rooms, rather than resulting in a change of the total airflow rate.

A better solution for AHUs covering many rooms is Pressure-controlled DCV, which has zone dampers on each branch (Figure 1.2). Each zone has a motorized damper controlled by a 0-10V signal from a pressure controller. The damper is controlled to maintain a constant pressure at the pressure sensor. The energy penalty to maintain a constant pressure in each zone is small if the pressure set point is set according to the minimum pressure requirements of the DCV dampers. This solution ensures that the minimum pressure in the AHU is suitable according to the DCV dampers' operational range.

The fan speed drive is controlled by a pressure sensor in the main duct.

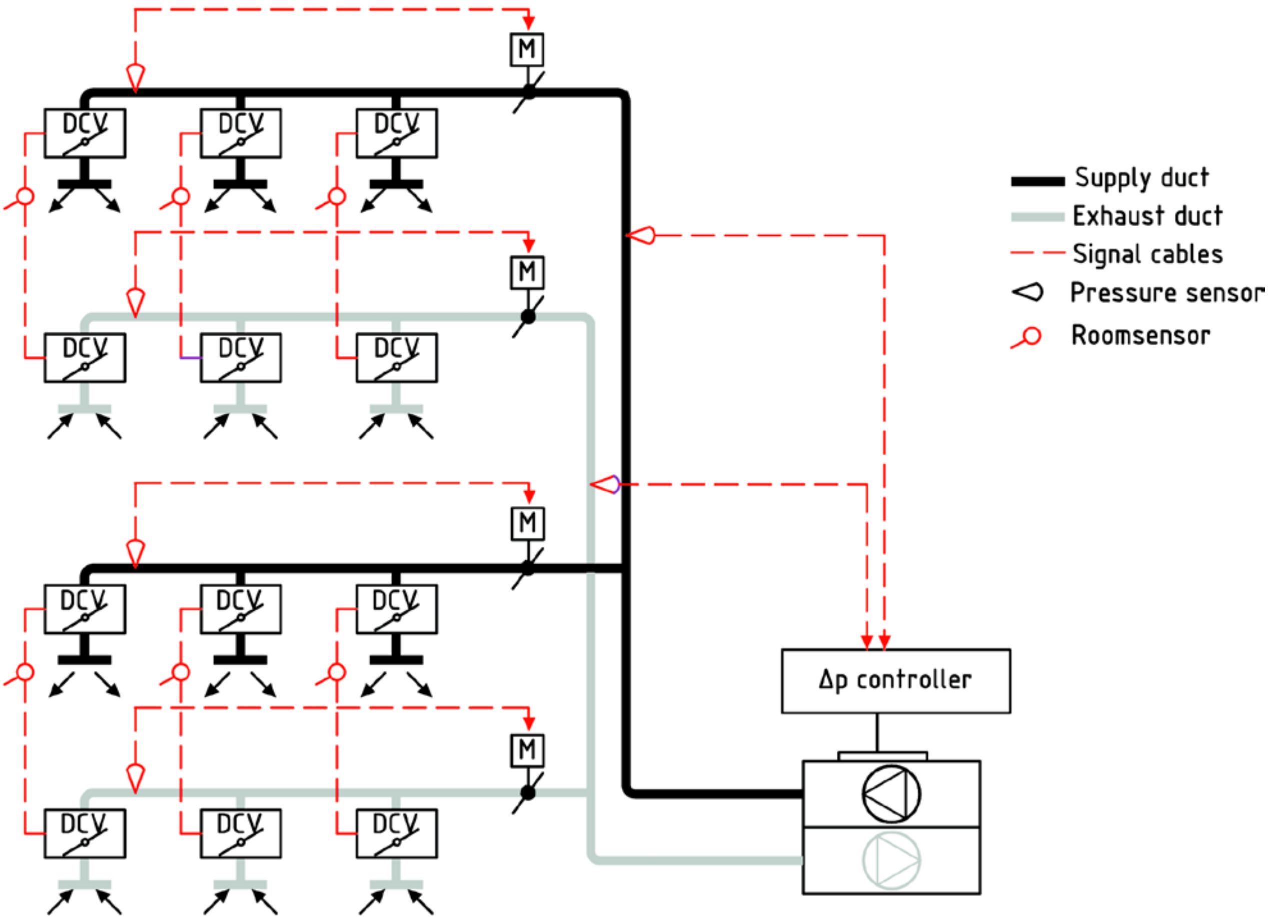


Figure 1.2 Pressure-controlled DCV with zone dampers.

1.3 Static Pressure Reset DCV

Static Pressure Reset DCV is a combination of Pressure-control and Damper-control (Figure 1.3). Each zone has a motorized damper that is controlled by a 0-10V signal from a pressure sensor. This damper controls the airflow rate in order to maintain a constant static pressure at the pressure sensor. A controller registers the angle of the damper and controls both the pressure set point in the main duct, and the fan speed, such that at least one of the zone dampers is in a fully open position.

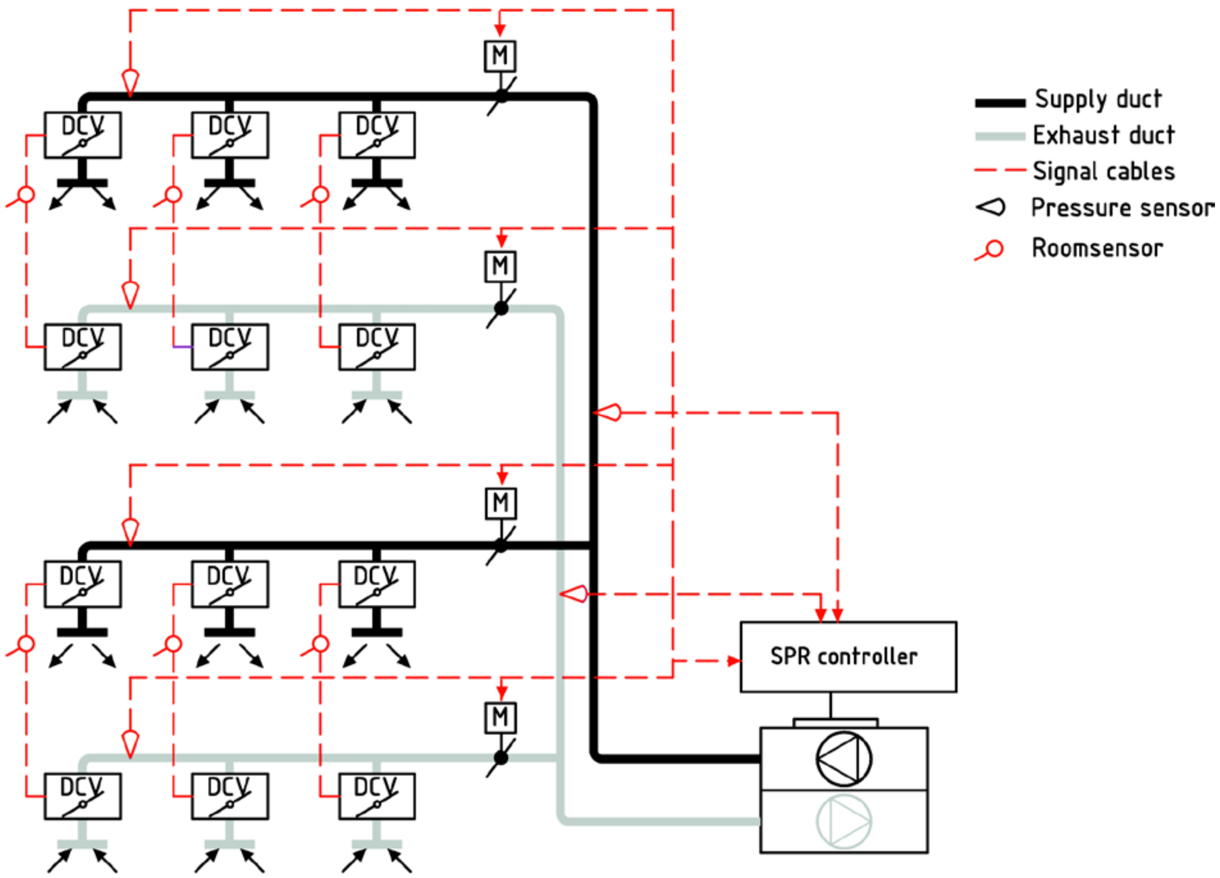


Figure 1.3 Static Pressure Reset DCV. The fan speed is controlled by a pressure sensor in the main duct, but the pressure set point is regulated by the controller such that at least one of the DCV dampers is in a maximum open position.

The «energy penalty» to maintain a constant pressure in each zone is small if the pressure set point is set in such way that the minimum airflow rate that the DCV dampers allow is reached. This solution ensures that the minimum pressure in the AHU is suitable relatively to the DCV dampers' operational range, while avoiding using energy to build up an unnecessary high duct pressure. With Static Pressure Reset DCV, the pressure sensor should be placed closer to the AHU than with Pressure-controlled DCV, see (Figure 1.3).

1.4 Damper-optimized DCV

Damper-optimized DCV consists in controlling the airflow rate in the main duct according to the position of the dampers, such that at least one of the dampers is in a maximum open position (Figure 1.4). The purpose is to ensure minimum fan energy consumption by applying a minimum pressure rise over the fan. This is achieved if a duct path (critical path) is always open. With damper-optimized DCV, the required airflow rate, the supplied airflow rate as well as the damper angle are recorded for all the DCV dampers. This information is sent to a controller which regulates the fan speed.

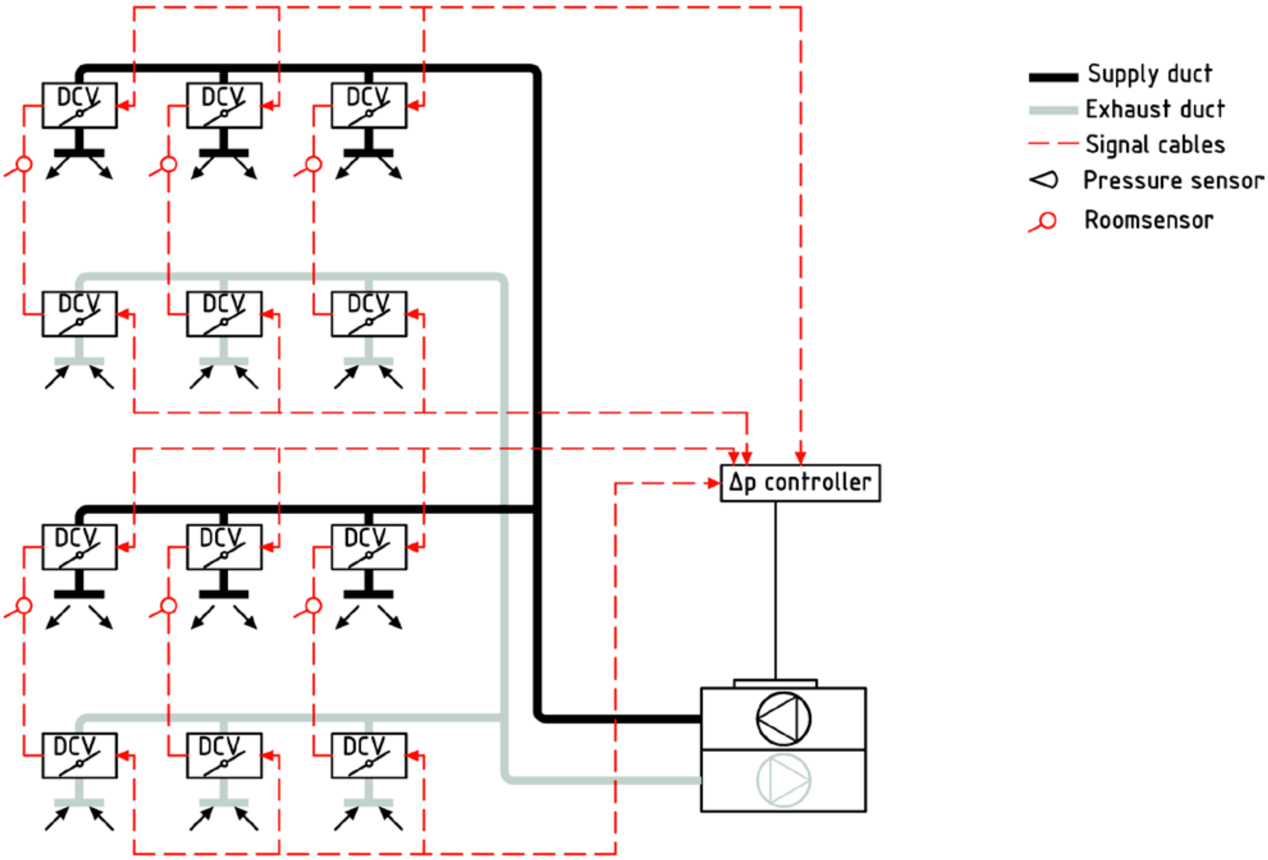


Figure 1.4 Damper-optimized DCV. Principle diagram without branch dampers.

In larger ventilation systems, one should consider to have a ZONE-VAV damper as shown on Figure 1.5, as well as branch controllers in addition to the main controller. DCV dampers within the same zone and corresponding ZONE-VAV are connected to the same branch controller. This branch controller records the required airflow rate, supplied airflow rate and damper angle for the all the DCV dampers and gives a signal to the ZONE-VAV in order to regulate the damper-opening so that at least one of the DCV dampers in the zone is in a maximum open position.

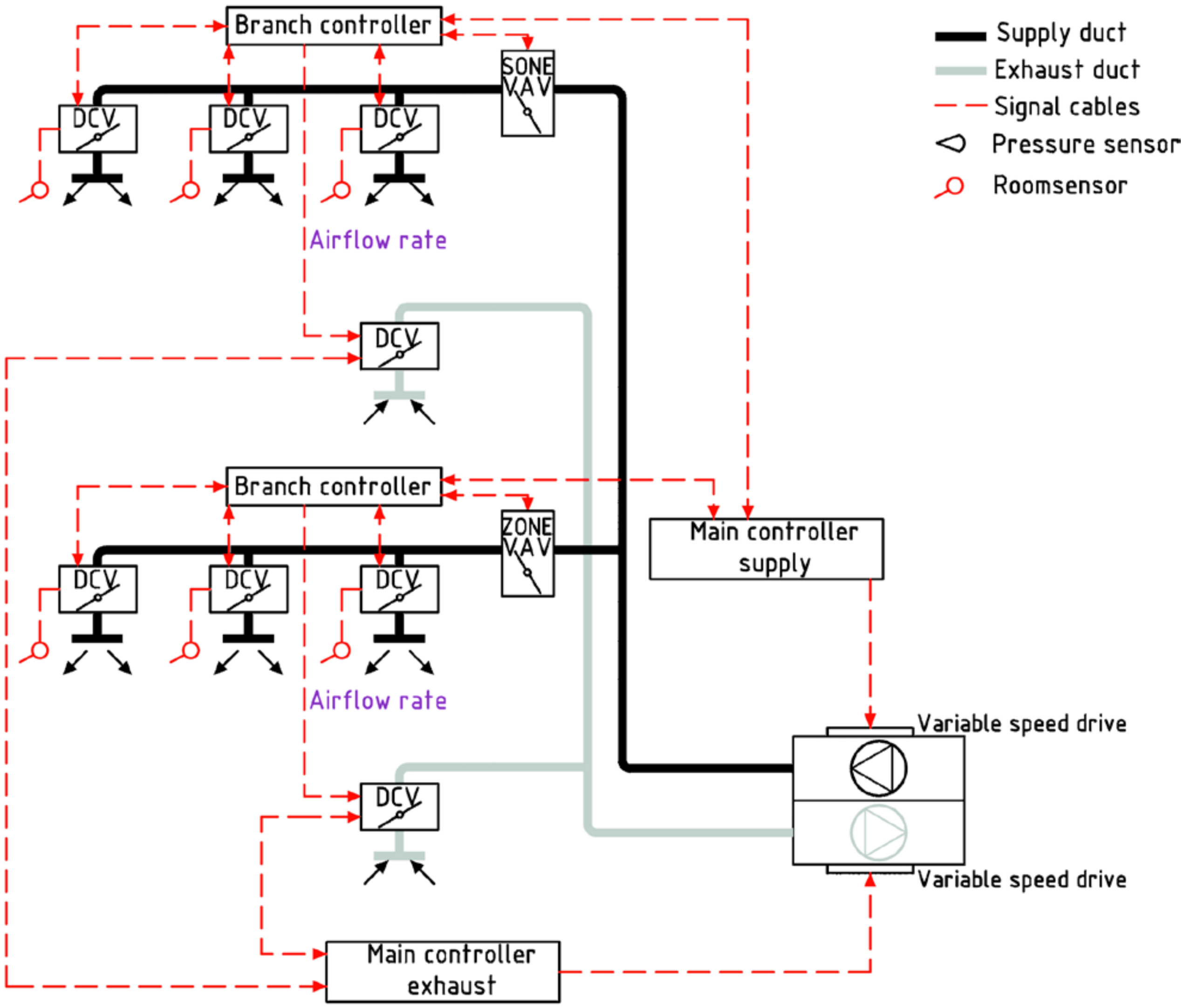


Figure 1.5 Damper-optimized DCV. Principle diagram with branch dampers and central exhaust.

Similarly, the main controller regulates the fan speed such that one ZONE-VAV is in a maximum open position.

It is also possible to program the control of the dampers directly in the Building Management System's controller instead of using branch and main controllers.

1.5 Variable Supply Air diffuser DCV

Using variable supply air diffusers (VSAD) is a possible variation of Damper-optimized DCV, where the DCV units are integrated in the air diffusers. Figure 1.6 shows a diagram where VSADs are regulated by a controller, and communication is performed via bus.

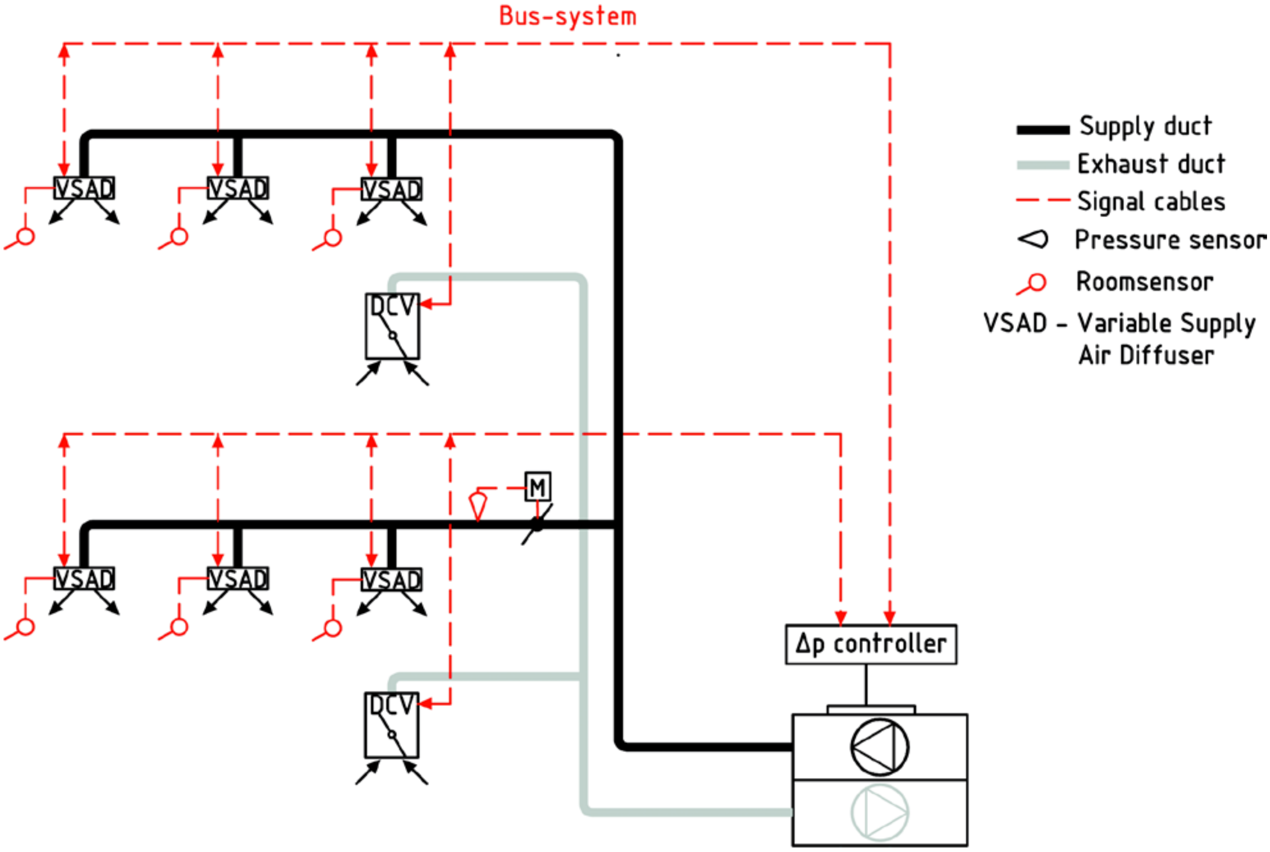


Figure 1.6   Schematic diagram with VSADs regulated by a main controller.

The controller records the required airflow rate, the supplied airflow rate and the damper angle for all the DVC dampers, and regulates the fan speed such that one of the VSADs is in a maximum open position on the supply side, and such that one of the DVC dampers is in a maximum open position on the exhaust side. The integrated motor-driven damper makes sure that the pressure remains in the working range of the VSADs. This damper should normally remain in a maximum open position and only throttle if the pressure in the duct becomes too high relatively to the working range of the VSADs. Such a situation can happen in the branches which are the closest to the fan in large ventilation systems.

1.6 Sensor alternatives

Sensors are a crucial element in DCV systems since they give the signal which is used to control the ventilation rate. The sensors should be resilient, and maintain a good accuracy over time and under actual working conditions.

DCV is possible with the help of sensors which measure one or more parameters, such as occupant presence, temperature, humidity, particles and various gas or gaseous mixtures. The most commonly used sensors for DCV are presented in Table 1.1, along with the benefits and drawbacks associated with the different sensors (Grini and Wigenstad, 2011).

Table 1.1 Common control parameters and sensor types for DCV

Control parameter	**Sensor type**	**Benefits**	**Drawbacks**
Clock	No sensor required. Possible to have time-control through the AHU or the BMS	Affordable	Not possible to control according to occupancy.
Presence	Motion sensor (IR-sensor)	Low cost Long life span	Limited possibility for gradual control according to actual occupancy, *e.g.* in meeting rooms, open space office etc.
CO_2 concentration	CO_2 sensor	Gradual demand-control according to actual occupancy in classrooms, meeting rooms, open space office etc.	Some types of CO_2 sensors can require calibration to ensure precise measurements over time. Large differences in measuring principles and measuring methods induce large differences in the quality of the measurements.
Temperature (in combination with one of the previous parameters)	Temperature sensor	Low cost Long life span	Only DCV according to heat loads.
VOC concentration	VOC sensor	Give the possibility to control according to measured Volatile Organic Compounds concentration. The latter can be used to predict a theoretical CO_2 level.	Unclear/hardly applicable requirements for VOC in relation to DCV. Cannot be controlled or calibrated. Accuracy as a CO_2 predictor not well documented.

Some types of sensors require frequent maintenance or calibration. This is for example the case for certain CO_2 sensors. Such a calibration procedure can be costly, and there is a risk that the calibration will not be carried out.

1.7 Control principles

The airflow rate is usually controlled according to three or four criteria depending on the hour, area (A) and the number of persons (n). The minimum requirements in terms of ventilation rate in Norway are presented in Table 1.2. These values are valid for occupants with a sedentary activity and buildings with very small emission of pollutants.

Table 1.2 Minimum ventilation rates in Norway (1 l/s = 3.6 m^3/h). Source: TEK10 (Kommunal- og regionaldepartementet, 2010)

Level	Criterion for the airflow rate	Typical airflow rate [m^3/hm^2]	Comment
1	Empty room outside of usage period	0,7 [m^3/hm^2] * A	This value is an average over the time period.
2	Empty room during normal usage period	2,5 [m^3/hm^2] * A	Assumes low emissions, good cleaning and no process contamination.
3	Occupied room with satisfactory temperature	2,5 [m^3/hm^2] * A + 26 [m^3/h] * n	Corresponds to the hygienic ventilation rate.
4	Occupied room with too high temperature	Temperature controlled ventilation rate which is higher than the hygienic ventilation rate.	

Generally, we recommend using DCV controlled with CO_2 sensor and temperature sensor in classrooms and other rooms with large variations in occupancy. Such a sensor can control the ventilation rate correctly according to the most important standards for indoor air quality (CO_2 < 1000 ppm) and thermal comfort (t < 26°C) (Norwegian Labour Inspection Authority, 2012).

It is the occupancy which determines the required airflow rate, and the CO_2 level above the outside CO_2 level is an indicator of the occupancy in the room. The production of CO_2 depends on the activity, the age and the size of each person. Adults produce 20% more CO_2 than children (Novakovic, et al., 2007). Since CO_2 is used as an indicator of the number of persons present, it is necessary to control the ventilation according to a lower CO_2 level in schools, for example 850 ppm rather than the 1.000 ppm recommended by the standard.

The outside concentration of CO_2 varies and is somewhat higher (around 20–25 ppm) during winter because of absence of photosynthesis and low natural carbon capture (Klima- og forurensningsdirektoratet, 2013). Since CO_2 is an indicator of the number of persons in the room, it is most precise and energy efficient to control the airflow rate according to a continuous measured difference between the CO_2 concentration inside and outside, as recommended by the EN15251 standard (2007). This requires to also measure the CO_2 concentration in the supply duct, or at the supply air intake, and to have a building control system which makes it possible to control the airflow rate according to the difference of the CO_2 concentration inside and outside.

The airflow rate should be controlled gradually according to an increasing CO_2 level, and not such that the lowest airflow rate is maintained until the maximum CO_2 limit is reached.

DCV should work simultaneously with the radiator heating load, to make sure that heating and cooling are not conducted at the same time.

2 Requirements and control

Recommendations in a nutshell:
When correctly implemented, DCV can reduce the energy consumption of ventilation by more than 50%. Setting proper requirements is crucial in order to reach this goal. We recommend a certain number of requirements. The most important are:

- maximum SFP for design airflow rate and defined reduced airflow rate
- compliance of the variation of airflow rate at room level and in the main duct
- documentation in the form of a functional description and a DCV diagram
- balancing and control of the airflow rate in the form of a completed control form for maximum and minimum load
- authority, accuracy and lifespan for the chosen sensors and DCV dampers
- maintenance and calibration-free CO_2 sensors
- good/suitable placement of sensors
- use of DCV dampers with robust pressure sensors relatively to soiling
- measurement of SFP before the frequency converters with a suitable method
- coordinated functional check for the whole ventilation system,

Expect deviations. Forecast time to improve the system. Agree in advance on an economic compensation scheme for the deviations from the requirements related to energy.

2.1 Background

2.1.1 Extent of control

The recommended requirements aim at providing a well-functioning and energy optimal DCV system. In order to be relevant, the control of the system at delivery should be confronted to the requirements which were initially specified for the system (Mysen et al., 2012) (Mysen and Schild, 2012). In short, you should:

- determine which requirements you want for the system, in terms of maximum and reduced airflow rate, energy consumption, etc.
- specify the requirements clearly to those who have the responsibility to deliver the system
- control that the delivered system fulfills the requirements

The time necessary for the control stage depends on the chosen technical solutions and on the possibilities to monitor and adjust the system. When a Building Management System (BMS) is available, it is possible to:

- have a functional monitoring in each room (airflow rate, damper angle/throttling, room temperature, duct temperature, CO_2 level, presence, light and shadings, influence from other local heating/cooling loads), DCV branches (airflow rate and damper angle/throttling)
- have good possibilities of adjusting the set points (temperature, CO_2, pressure)
- continuously record airflow rate and SFP

It is largely possible to balance the system and provide a functional documentation directly with the help of the BMS. It can be sufficient to set requirements for a pre-programmed automated load test as described in Chapter 5.4. When that is not possible, one has to simulate the desired load directly on the AHU, and control room after room. This control must be carried out for the extreme points of the operating range (both minimum and maximum load). It is described in Chapter 5.

A DCV system should supply a quantity of air in agreement with the actual needs, with sufficient accuracy and sufficiently short time constant. This is necessary in order to ensure a good indoor climate while minimizing energy use. The balancing time of the ventilation system should be controlled after a change in the system.

2.1.2 Documentation

There should be clear requirements for documentation, both in terms of extent and content. DCV systems adapt themselves according to the actual load (temperature, CO_2, presence, lighting and shadings, influence from other local heating/cooling loads) and the airflow rate should be controlled correctly in relation to this. In many cases, different zones interact, for example when the airflow rate on a common exhaust is too high, and the supply and exhaust have to be balanced. This constitutes a dynamic which quickly gets complicated. This functional dynamic have to be planned and communicated on from the design phase to the construction phase. Both the operation staff and those who will further develop the system in case of refurbishment/change of the building should get the proper information. This requires a thorough functional description and an automatic controls diagram which displays the communication at room, zone and system level.

2.1.3 Airflow rate and simultaneity

What is considered as normal operating range and maximal and minimum airflow rate is dependent on each project. Minimum airflow rates are specified in the Norwegian building regulations TEK10 (Kommunal- og regionaldepartementet, 2010). Their calculation is based on several assumptions and requirements regarding pollutant emissions and temperature control. In TEK10, the minimum airflow rate outside of operating hours is 0.7 m^3/hm^2 (1 l/s = 3.6 m^3/h), and 2.5 m^3/hm^2 in operating hours when the room is not occupied. When the room is occupied, the minimum airflow rate becomes 2.5 m^3/hm^2 + 26 m^3/h/person. Normal operating hours for school is defined in NS 3031 as 10 hours/day, 5 days/week, and 44 weeks per year (table A.3 in NS 3031). A review of 157 classrooms in Oslo showed that the classrooms are occupied in average during 4 hours during the operating time (Mysen, et al., 2005). This occurs mainly in the period from 8.30 to 14.00. In this time period, one can expect that all the classrooms are occupied (Mysen, 2012). In addition, control of the airflow rate according to temperature should provide maximum simultaneity even if all the classrooms do not have a maximal occupancy at the same time. **It is therefore not recommended to under-dimension the ventilation system because of simultaneity in schools.** Outside of this time period, the system should provide the minimum airflow rate, when the latter is not controlled by temperature. This means that the average simultaneity over the operating time can be below 50% in primary schools. However, this depends on the minimum airflow rate and operating time. It is important to select fans and a control strategy which present a good efficiency in the whole operating range.

The airflow rate outside of the operating time can be under 10% of the AHU's capacity if we consider TEK10 and the base value of 0.7 m^3/hm^2 in schools. Traditional ventilation systems cannot control the airflow rate to such low values. It is then relevant to consider the minimum airflow rate as an average over a period of time when the ventilation is running and a shorter period without ventilation, *i.e.* intermittent operation. The ventilation should not stop when the school can be occupied. This is particularly important if there is a risk of radon infiltration from the ground. Schools are often used during evenings (Mysen, 2012).

2.1.4 Airflow rates and demand-control with CO_2

People exhale carbon dioxide (CO_2), and a common DCV strategy consists in regulating the airflow rate of fresh air according to the indoor CO_2 level. It is important to note that the ventilation's aim is not solely to reduce the CO_2 level, but to compensate for the emissions of the occupants, whose presence is indicated by the CO_2 level. The CO_2 level in a room depends on the CO_2 concentration in the outside air, the exhaled air from the occupants, the supply airflow rate of fresh air and the ventilation efficiency in the room.

The CO_2 concentration in the outside air varies between 380 and 450 ppm, depending on the location, time, pressure and temperature. In addition, the CO_2 level rises by around 2–3ppm each year because of emissions from fossil fuels (Klima- og forurensingsdirektoratet, 2013).

If the airflow rate is controlled towards an absolute CO_2 level of 800 ppm, the ventilation will in practice increase from 13 l/s*person in the summer period to 14 l/s*person in the winter period. In addition, the airflow rate will rise by approximately 1 l/s every 14 years because of the rise in outside CO_2 level.

The amount of CO_2 which is emitted by people is thought to be proportional to the emission of bio-effluents. It is the latter that we actually wish to control by supplying fresh air. Therefore, it is necessary to continuously measure the difference between the outside and inside CO_2 concentration, and to control the ventilation rate according to this value, as recommended by the EN 15251 standard (2007). This implies to also measure the CO_2 concentration in the supply duct or at the fresh air intake, and that the building automatic system controls the airflow rate according to the difference in CO_2 level.

If the building's operation and utility model allows the use of self-calibrating, it is necessary that the outside and inside sensors are of the same type, and that they have the same self-calibration procedure. The outside sensor should be in the same thermal conditions as the indoor sensor, for instance located after the heat recovery exchanger on the supply air section.

2.1.5 Use of Specific Fan Power (SFP)

It is important to clearly specify requirements in terms of SFP in order to get an energy efficient DCV system. DCV systems are not necessarily energy efficient. Figure 2.1 shows the variation of SFP according to the airflow rate for an ideal, good, normal and poor ventilation system, respectively (Schild and Mysen, 2009). The differences lie in the fact that some systems regulate the airflow rate by using unnecessary throttling.

The SFP is an appropriate value to set requirements to, which can be controlled and therefore ensure an energy optimal solution. This implies to define beforehand how SFP should be measured and how the measurement uncertainty should be evaluated.

In order to reach minimal energy use, the fan efficiency should be maximal at average pressure drop in the ventilation system.

2.2 Recommended requirements for energy consumption and airflow rate

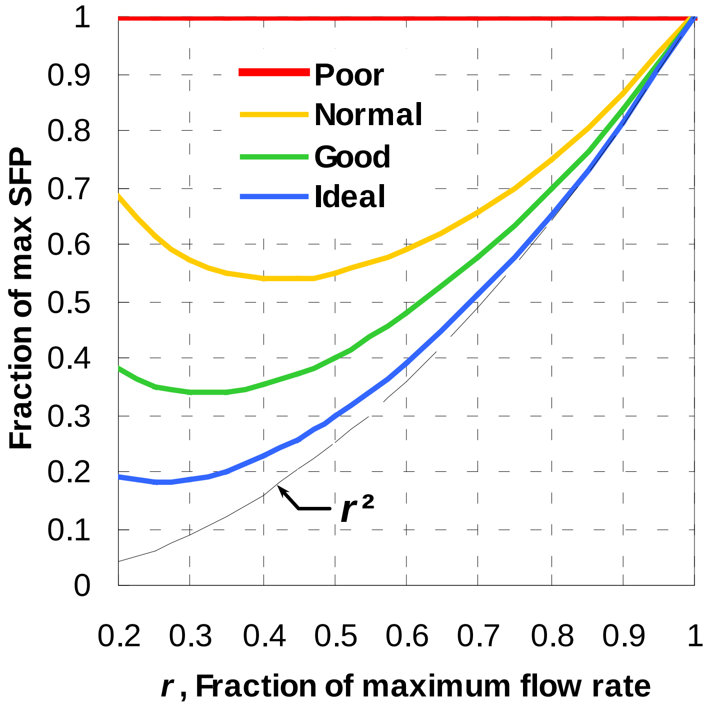


Figure 2. Illustration of the co-variation between airflow rate and SFP for Poor, Normal, Good, and Ideal DCV systems.

2.2.1 SFP-requirements for maximum and reduced load

SFP is usually measured for maximum load, *i.e.* for design airflow rate and pressure drop. For this control point, the different control strategies will give roughly the same SFP value. In order to control if the system regulates efficiently in terms of energy consumption, the system should also be controlled for partial load (Figure 2.1).

The procedure for measuring SFP should be defined at the same time as the requirements for SFP are set. This is done either during the requirement specification or in the description of the offer. We recommend following the method described in 2.6.2 and 2.7.2.

Set requirements for SFP both for design conditions and partial load. Alternatively, you can request that the system follows the blue line, or that at least one of the DCV dampers is in maximum open position when the system is in stable conditions. This implies that the percentage of opening of the DCV dampers should be recorded, as well as the airflow rate downstream of the DCV dampers.

2.2.2 Airflow rate measurement at AHU level before and after a known change in the zone

One of the objectives of DCV is to reduce the airflow rate and the energy consumption in rooms which are not used as designed. When one room is left unoccupied, the change should be captured by a sensor in the room. The sensor then gives a signal to the DCV damper associated to the room, in order to reduce the airflow rate in accordance with the new demand. For a pressure-controlled system, this change must be captured by a pressure sensor which induces a correspondingly reduction of the main airflow rate. That this happens in practice is not guaranteed, and depends among other things on the pressure sensor placement and sensitivity. It is therefore important to require that a change of airflow rate at zone/room level induce a corresponding change of the main airflow rate, and verify that this is the case during commissioning.

Set requirements for the relationship between change in airflow rate at room level and change in main airflow rate. A reduced airflow rate at room level should result in a corresponding reduction at AHU's level. We recommend to control the airflow rate at room level in a way that it corresponds at minimum to 5% of the total airflow rate, and to allow a deviation of ±30 % at the AHU's level according to the measured airflow rate at room level. For example, an AHU with 10.000 m^3/h should be controlled with a minimum reduction of 500 m^3/h at room level. This corresponds to a reduction between 350 and 650 m^3/h at AHU level.

2.3 Recommended requirements for documentation

2.3.1 Summary

A DCV system should be handed over with at least:

- a functional description
- a DCV diagram showing the automatic controls' principles
- a completed VAV control form (at room/zone level)
- values from SFP measurements for defined maximal and reduced load
- values from airflow rate measurement at AHU level before and after a known change in the zone
- a protocol for coordinated functional check

2.3.2 Functional description

The functional description should clarify how the DCV system works in the whole operating range in order to provide an airflow rate which satisfies the demand and how the ventilation works in coordination with the other air conditioning systems (heating and cooling systems, window ventilation, venetian blinds control etc.). A good functional planning incorporated in the functional description is essential to obtain a well-functioning DCV. Typical elements included in a functional description are:

- type of system/solution principle
- coordination between sensor values, room control, zone control/regulators, function at system level and control of the fan speed
- coordination between systems
- function/ventilation control at zone and room level
- zones with overpressure/underpressure
- type of sensors and placement
- set points at the beginning of operation (CO_2, temperature level etc.) and how the set points vary during operating time

- signal priorities for the different sensors
- requirements in terms of accuracy, and possible measures to take into account temperature phasing in order to exploit the thermal mass, and which constraints this implies for the temperature set point
- various minimum levels (during and outside of operating time)
- maximum level
- chosen simultaneity both for design and energy calculations
- common wiring of sensors, for example via modular solutions in adapted areas with flexible switch between office landscapes and cubicles
- coordination of supply and exhaust, for example when a common exhaust is used
- compensation for outside CO_2 level
- description of troubleshooting in operating phase and further development in case of modification of the building/change of function

In addition, the bus protocol should be described: open or proprietary systems, communication solutions at various levels, Web server or PC, user interface, which signals which must be monitored and thus logged, the exporting of data to the Energy Monitoring System (EMS) and major alarms.

The functional description is an important foundation document during the detailed design stage, while choosing the automatic controls, for the pricing/offer, as well as during installation, handover, performance checks, and to guarantee a good operation.

2.3.3 DCV diagram illustrating the automatic controls

A DCV diagram shows the relationship between DCV control, heating control, light control and any other interacting systems. This relationship can be showed using a figure of the system, an automatic diagram or a topologic diagram. An example is shown in Appendix A.

2.3.4 Completed VAV control form

A major part of the work on the final inspection consists is a load test with associated VAV control form, as described in Chapter 5. This should be done as well for demand controlled systems which do not fit in the DCV definition, hence the name «VAV control form». Balancing of the pressure set point and control of SFP for maximal and reduced airflow rate can be carried out at the same time as the load test.

Experience shows that virtually all DCV systems where control of the airflow rate is not correctly performed present failures in the operating phase which affect indoor climate or energy use. In fact, there is a strong interdependence between the thoroughness of the final inspection and the number of errors in the delivered DCV system.

When spot-testing (random sampling) is used, an agreement should be made regarding the number of measurements necessary to guarantee that a good control is achieved. It is also important to repeat the functional check after any correction or modification of the system.

During the design of the automatic controls, it is important to make it possible to easily be able to override the DCV units in the system. If this is not done, the load test at partial load and at maximum load will be very time consuming and expensive, and in the worst cases not possible to carry out. In addition, it would then be difficult to detect errors in the operating phase.

2.4 Requirements and control for the other components

2.4.1 CO_2 and temperature sensors

A sensor in a DCV system should have a satisfactory accuracy in all of it's specified lifespan. The sensor should be selective (not respond to unauthorized gases). In addition, it should be robust in relation to the chemical, mechanical and thermal influences it is exposed to.

The sensor should be documented according to the following questions:

- How will the sensor be controlled during operation?
- How often does the sensor need to be calibrated and how?
- How does the sensor react to dust and soiling?
- How accurate are the measurements provided by the sensor?
- What is the maximum measurement error for the temperature sensors and CO_2 sensors under actual operating conditions?
- What is the lifespan of the sensor and how is the lifespan documented?

Different calibration requirements can have a significant impact on the operating cost. We recommend maintenance free or self-calibrating CO_2 sensors. If sensors which require manual calibration are chosen, the cost implication should be included in order to make products economically comparable. The supplier should also indicate the need and requirements for recalibration. Calibration costs can quickly become greater than the purchase cost.

Requirements should be specified regarding the maximum deviation of the CO_2 sensors. The current quality standards in California (Commission, 2010) require a maximum deviation of ± 75 ppm during the first 5 years after installation.

We suggest the following requirements:

- maximal uncertainty for CO_2 sensors in the range 300 to 1200 ppm: **+/- 50 ppm**
- maximal uncertainty for temperature sensors in the range **0– 40 °C: +/- 0,5 °C**
- expected lifespan for CO_2 sensors without calibration or other maintenance: **15 years**

If the CO_2 sensor is placed at the exhaust, there should be one sensor per room. It should be placed immediately after an exhaust terminal device. It should be clearly marked and easily accessible for inspection and maintenance. A prerequisite to place the sensors in the exhaust is that the conditions at the exhaust should be representative of the condition in the room. For example, a low ventilation rate and presence of internal heat loads can result in a higher temperature at the sensor than in the room. In this case, DCV based on temperature control cannot work.

We recommend carrying out annual check of CO_2 sensors using the BMS to detect unnatural deviations and sensor errors. This can be done by running the ventilation system at the lowest airflow rate when the building is not in use. Measured values should then represent the outdoor CO_2 level and be approximately equal. If the recorded deviations are higher than required, the sensors should either be checked and repaired, or new measurements should be carried out with increased airflow rates. Possibly, the minimum airflow rate could be increased to make sure that the minimum required airflow rate is provided even if the deviations are higher than required. Such a measure results in an increased energy cost.

2.4.2 Presence detector/ motion sensor

Motion sensors must have an adequate detection range in each room. If necessary, several motion sensors should be placed per room. Roof-mounted motion sensors should have a 360 ° detection angle.

2.4.3 Pressure sensor

It should be possible to set the pressure range directly on the pressure sensors. It is important that the pressure sensor does not have to work in a too large range, as this will cause inaccurate pressure measurements. Static pressure sensors should be used where there is a risk of dust in the air stream. Pressure sensors must be placed in a suitable location with stable static pressure. A temporary solution is to use pressure sensors with adjustable signal damping in order to reduce the cyclic variations when it is not possible to measure a stable static pressure.

2.4.4 DCV dampers and airflow controllers

Use DCV dampers with pressure sensors which are robust towards dust exposure, for example static pressure sensors.

DCV dampers usually have settings for minimum airflow rate during normal operation (V_{min}) and maximum airflow rate (V_{max}). If a lower minimum airflow rate is desired outside of normal operation, it should be specified.

Requirements should be specified for the maximum measurement uncertainty of the DCV dampers, both for normal and nominal airflow rate (10–15%). The supplier should also provide the measurement uncertainty at minimum airflow rate since a large uncertainty can have a significant impact on energy use when many rooms are empty.

The supplier should have clear requirements for the placement of the DCV dampers in terms of flow obstacles in the duct system. Distance requirements before and after the DCV units may vary between different products. It is important to be clear about any physical limitations in the project, which could make some products unsuitable.

Many DCV systems do not work correctly because mechanical CAV dampers are mounted in a system with DCV. These dampers are dependent on a high pressure to be able to work, and should not be used together with DCV dampers. We recommend using DCV dampers also in zones with constant airflow rates such as toilets, changing rooms etc. The required constant airflow rate is programmed into the DCV damper as minimum airflow rate. The damper then only requires operating voltage (no room sensor) in order to maintain the desired constant ventilation rate.

2.5 Coordinated functional check

A well-functioning DCV system is the result of a successful interaction between system design, component selection and automatic controls. Often, the ventilation and automation contractors are different, and the coordination between these two is a challenge. Moreover, it can be another HVAC contractor which provides the heating and cooling systems. There should be a coordinated functional check at ventilation or air conditioning level. The functional check should be carried out at room level, zone level and AHU level. The completion of the VAV control form can be done during the functional check. All coordinating systems must be completed before the functional check. Heating and cooling systems must be commissioned when temperature controlled DCV is used, which applies to most systems.

It is appropriate to control SFP during the functional check.

Furthermore, DCV systems should be able to work in all operating conditions. This cannot be controlled before the system has actually worked in all seasons. Thus, the functional check should be repeated after one year of operation.

The coordinated functional check should be included in the offer description for all the contractors who are involved. An entrepreneur should be assigned responsibility for the coordinated functional check and be allowed to price this as a separate item. Part of the contract sum should be withheld until the last coordinated functional check is completed and approved. Responsibility for function and corrective measures should be clearly defined, either through a transport of obligations, or in a joint technical contract.

Transport of obligations means that another contractor will be subject to the general contractor, and a new contractual relationship is established between them (subcontractor contract). Transport of obligations entitles to transfer risk and administrative tasks to the new subcontractor.

It is often two contractors, automatic controls and ventilation, who deliver components and solutions which influence the resulting indoor climate. When a deviation occurs between the actual and required system performances, it is often difficult to determine who is responsible for the observed deviations between these two contractors. When transport of obligations is used, the two contractors are subject to a head contractor, or one of the two contractors is defined as head contractor, with all responsibilities to deliver what has been required.

2.6 Control of Specific Fan Power

2.6.1 Challenges

It is important that SFP is controlled for different AHU loads to ensure that the installed system is energy efficient. The AHU should be designed such that it is possible to measure SFP directly.

The VAV control form has its own box for control of SFP, and it is appropriate to carry out the SFP control after the control of the airflow rate for maximum and minimum conditions, respectively.

2.6.2 Recommended methods

We recommend measuring SFP on the switchboard, before the commutator transformer, in order to include all the losses in the measurement. SFP can be measured with a suitable three-phase power analyzer, by using the two-Wattmeter method, or the three-Wattmeter method (see Appendix D). The measurements should be carried out at the same time as the airflow rate measurements, in order to ensure that SFP is measured for the appropriate airflow rate. We recommend measuring SFP with a three-phase power analyzer rather than with the two-Wattmeter method for the following reasons:

- 3-phase power analyzers can show a 3-phase diagram. This gives an immediate visual indication when the measurement wires have been connected in the wrong order.
- It is possibly more accurate (according to calibration tests conducted by Nemco in Norway). This is also reflected by the high price of 3-phase analyzers.
- It provides measurements on all phases simultaneously, which excludes errors due to an unstable airflow rate, which may be a problem with the two-wattmeter method.
- It can log SFP over time.
- It can save screen dumps, which is very useful in busy field-measurements of many AHUs.
- The user avoids the need to do any calculation (for 2- or 3-watt methods calculations, the user has to add the powers on each phase). This reduces the risk for manual errors.

2.6.3 Evaluation of uncertainties

Not enough measurements of SFP have been done in order to statistically evaluate the uncertainties associated to such measurements. Therefore, the uncertainties should be evaluated using other sources, such as the calibration certificates or the technical specifications from the manufacturer. When provided, the statistical distribution and standard deviation can be calculated.

2.7 Control of airflow rate

2.7.1 Challenges

It is important to control SFP for different loads on the AHU, in order to make sure that the installed ventilation system is energy efficient.

This means that several measurements are necessary, and that it should be possible to carry them out in a quite easy way. It should be possible to override the AHU in order to obtain the desired load, which should be achievable without much trouble. A possibility would be to allow overriding the AHU through the Building Management System, or equivalent.

If pressure measurements have to be performed in order to assess the airflow rates, the AHU should have pressure outlets which are easily accessible.

2.7.2 Recommended methods

The measurement of the main airflow rate should be performed, inside, or close to the AHU. A pressure outlet is usually mounted before the fans in the AHU, which allows measuring the airflow rate over the fans (Figure 2.2).

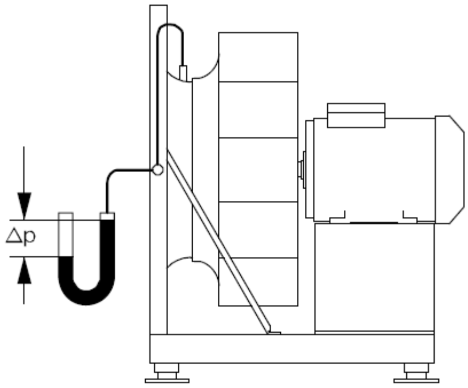


Figure 2.2 Measurement of the airflow rate with the pressure outlet at the entrance of the fan.

2.7.3 Assessment of measurement uncertainties

Measurement uncertainties can be calculated according to the following equation:

$$m_{tot} = \sqrt{m_i^2 + m_m^2 + m_r^2}$$

Where:

m_{tot} is the total uncertainty [%]

m_i is the instrument error [%]

m_m is the method error [%]

m_r is the reading error [%]

The instrument error is provided by the manufacturer. The method error is provided for standardized methods. The reading error must be determined for the actual measuring equipment.

2.8 Compensation in case of deviation

2.8.1 Background

Final inspection of the ventilation systems is done late in the construction project and there is usually not enough time to correct errors. Therefore, it is more appropriate to have a financial compensation in order to make up for the deviations between the requirements and the actual performances. We recommend having a reciprocal compensation that is based on the value of SFP measured during control, and on the associated energy use for the AHU during the 10 first years of operation.

The energy use can be estimated using the following equation:

$$Airflow\ rate\ \left(\frac{m^3}{h}\right) \times SFP\ \left(\frac{kW}{m^3/s}\right) \times \left(\frac{1\ h}{3600\ s}\right) \times Operating\ time\ \left(\frac{h}{y}\right) = Energy\ use\ \left(\frac{kWh}{y}\right)$$

2.8.2 Example of a simplified compensation scheme

Let us consider an AHU which supplies on average 10.000 m³/h, 3.000 hours per year. The requirements for SFP were 2,0 kW/(m³/s) for defined measuring conditions which we assume correspond to average operating phase. Control measurements show that the actual SFP value is 1,6 kW/(m³/s).

This good SFP-value induces a saving of 3.333 kWh in fan energy use each year:

$$10\,000\ \frac{m^3}{h} \times (2 - 1{,}6)\ \frac{kW}{m^3/s} \times \left(\frac{1\ h}{3600\ s}\right) \times 3000\ \frac{h}{y} = 3333\ \frac{kWh}{y}$$

With an energy price of € 0.1/kWh, the entrepreneur should receive € 3.333€ × 10 year = € 3.333,- in disbursement, assuming a mutual compensation that is based on the difference between the required and measured SFP.

2.8.3 Example of a current value based compensation scheme

A more accurate compensation scheme can also be used, based on the current value of future savings with predefined interest rate, lifespan and energy price evolution. The table below shows an example of such a current value based compensation scheme.

Table 2.1 Example of calculation of compensation scheme with current value method

	Full operation, 100 % presence	Uncertainty [%]	Average during reduced operating phase	Uncertainty [%]	Unit
Required SFP	2	-	1.34	-	[kW/m³/s]
Measured SFP	1.5	12	1	12	[kW/m³/s]
Deviation SFP	0.5	-	0.34	-	[kW/m³/s]
Deviation SFP	25.0	-	25.4	-	[%]
Airflow rate	22000	-	15620	-	[m³/h]
Operating time office	1560	-	1560	-	[h]
Energy cost	0.076	-	0.076	-	[□/kWh]
Annual cost	362	-	175	-	[□]
Total	537	-		-	[□]

Lifespan AHU	15	[year]
Cost AHU	200	[□/m²]
Area	600	[m²]
Interest rate	3.8	[%]
Cash flow	537	[□]
Total cost	120000	[□]
Compensation	6057	[□]
Net current value	6057	[□]
% of total cost	5.05	[%]

Part 2 Work stages for various DCV systems

3 Work stages

Recommendations in a nutshell:
After mounting of the ventilation system, several work stages should be performed in order to obtain a system that is ready for handover and operating phase. Each step should be completed before the next one can begin.

The commissioning, balancing, and control of a DCV system consist of the following work stages:

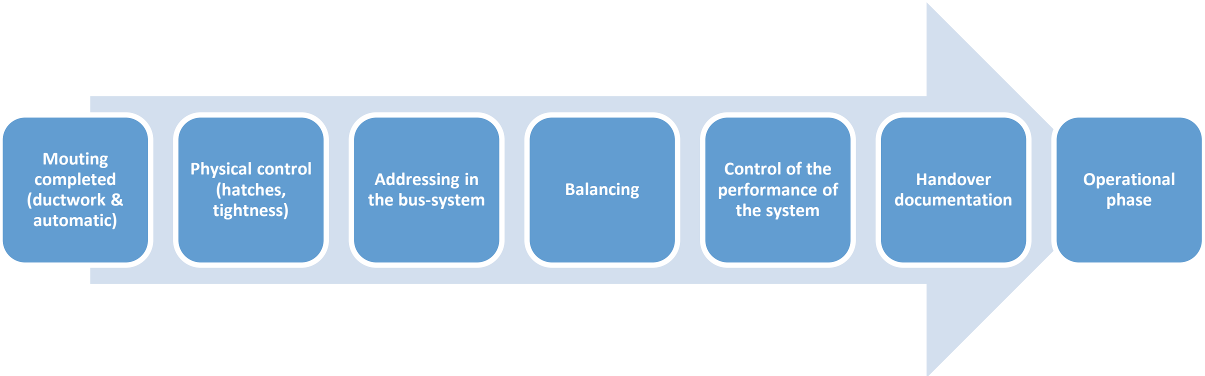


Figure 3.1 Recommended work stages subsequent to the mounting of the ventilation system

The following sections deal with the tasks in these work stages which are specific to DCV.

In order to reach the expected quality, each step must be fulfilled before the next one can begin.
For example, it is out of question to perform a pressure test on a ductwork before all the branch connections and inspection hatches are installed. Another aspect is that it is not possible to control the performance of the system and carry out a load test related to DCV if the whole ventilation system is not operational.

Addressing is not considered further in detail in this guide, since addressing method are specific to each ventilation supplier. Each DCV unit is delivered with a unique ID (for example a sticker and a barcode). Addressing consists in registering these IDs in the controller (bus system) such that the controller can allocate the individual messages to the specific DCV units. This can be performed either by the automatic controls or the ventilation contractor. Addressing error may occur, for example if two DCV units are switched. This would normally be noticed during a rigorous load test, which is described in Chapter 5 of this guidebook. In order to minimize the risk for such error, it is recommended to carry out the addressing in the most automatic way, for example with an addressing button on the DCV units.

4 Balancing method for the different strategies

Recommendations in a nutshell:
Pressure controlled DCV must be balanced in the following way:
- control the placement of the pressure sensor
- set the right pressure set point
- adjust the control dampers in VAV systems with fixed control dampers according to the proportional method

4.1 Balancing for pressure-controlled DCV without optimizer

Figure 4.1 shows the supply air section of a simple pressure-controlled DCV system. Balancing a pressure-controlled DCV system consists in:
- controlling the placement of the pressure sensor
- setting the right pressure set point

Later on, the balancing stage will reveal connection and communication errors. A part of the balancing process is similar to the balancing of a CAV system (Constant Air Volume) with proportional method. A description of the proportional method is given in appendix C and the underlying concepts are explained in Chapter 8.

Balancing of a pressure-controlled DCV system consists of the following steps:
- Control that all the DCV units have supply voltage and no polarity error.
- Control that the pressure sensor is mounted on a location with stable static pressure or uniform velocity profile, by performing measurements over the duct cross section with a Pitot-tube or a hot-wire anemometer.
- Select a pressure set point which is slightly higher than necessary. This can be deduced from pressure drop calculations or empirically.

Well-designed responsive systems which are composed of DCV zones can be balanced in the following way:
- Define the design maximum and minimum airflow rate for each DCV damper and set the dampers to automatic mode. Control that all the DCV dampers get the maximum airflow rate, and read the opening grade. Find the index damper, which is the damper with the highest opening grade.
- Reduce the pressure set point until the index DCV damper gets the maximum airflow rate without throttling (maximum open position). You have then found the energy optimal pressure set point, which is the lowest pressure set point which provides the right airflow rates according to the designed values.
- Complete the VAV control form.

For more complex and slow responsive systems, we recommended the following procedure:

- Open all the dampers completely and lock them in this position. The best is to require that all the DCV dampers have a programmed balancing procedure which opens all the dampers. The DCV units should be blocked at the maximum open position, *i.e.* around 80%. An alternative is to simulate a situation where the dampers are asked for more air than they can give, in order to get them in maximum open position.
- Lock the fan speed. The fans should be blocked around the design airflow rate before it is possible to decide upon the pressure set point.
- Carry out preliminary measurements. Fill up a VAV control form with the design maximum and minimum airflow rate values for the DCV diffusers. Calculate the ratio of the measured airflow rate to the design airflow rate for each diffuser. Find the index diffuser (the one with the lowest ratio).
- Reduce the pressure set point until the index DCV diffuser gets the maximal airflow rate without throttling (maximum open position). You have then found the energy optimal pressure set point which is the lowest pressure set point which provides the right airflow rates according to the designed values.

Finally, the actual maximum and minimum airflow rates values (V_{max} and V_{min}) are programmed on each DCV damper. The automatic controls are activated and the DCV dampers are set in AUTO-mode. The VAV control form (figure 5.1) is completed after the balancing, or during the functional check. The completed control form should be included within the documentation of the ventilation system.

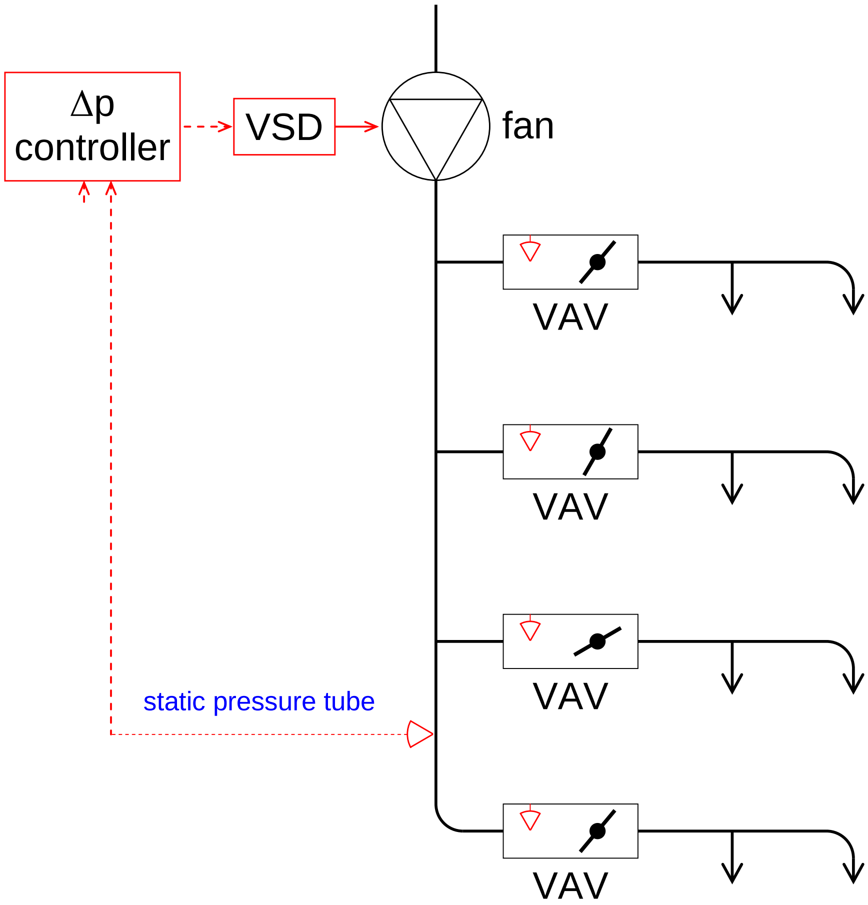


Figure 4.1 Supply air section of a simple pressure-controlled DCV system.

4.2 Balancing systems with both DCV dampers and CAV dampers

Figure 4.2 illustrates the supply air section of a pressure-controlled DCV system with both DCV and fixed manual dampers (without airflow controllers , also named «CAV»). Balancing such a ventilation system consists in:

- controlling the placement of the pressure sensor
- setting the right pressure set point
- balancing the manual dampers/diffusers

Later on, the balancing stage will reveal the connection and communication errors.

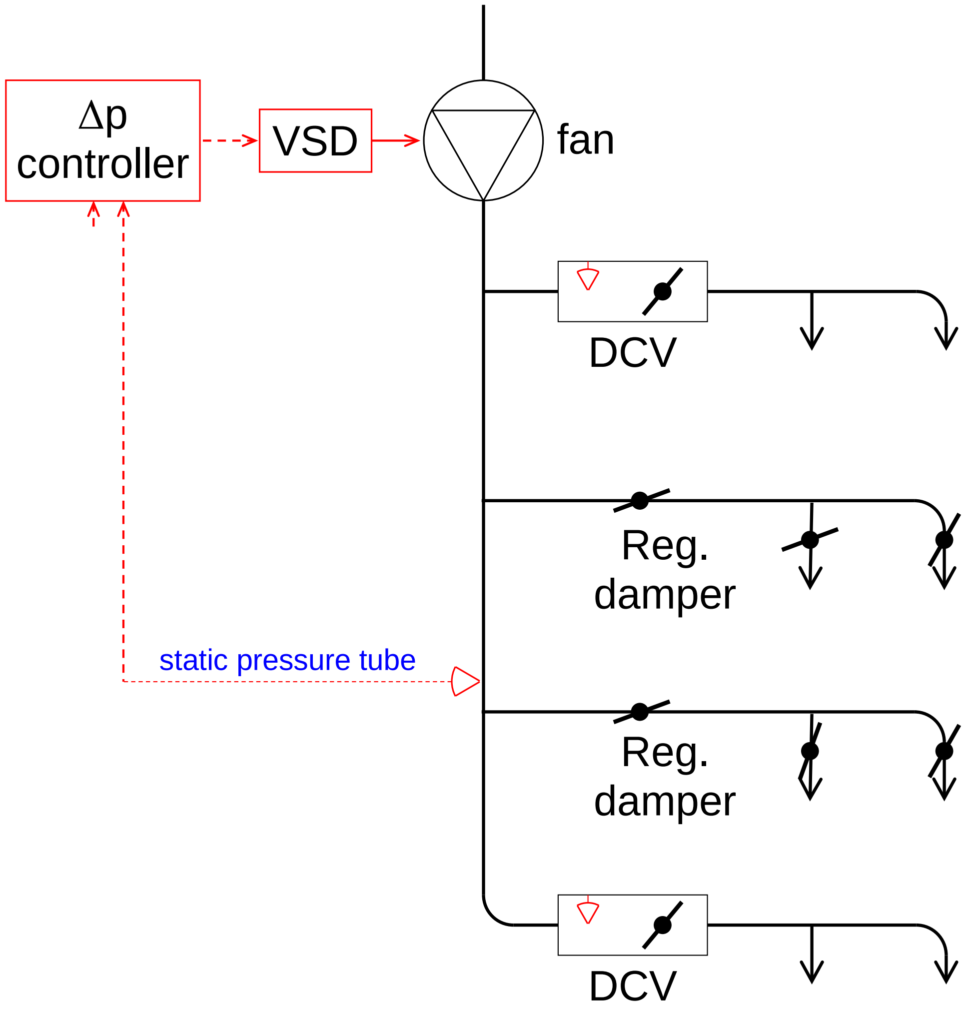


Figure 4.2 *Schematic diagram showing the supply air section of a pressure controlled DCV system with manual dampers.*

The balancing of such a ventilation system consists of the following steps:

- Control that all the DCV units have supply voltage and no polarity error.
- Select a pressure set point which is slightly higher than necessary. This can be deduced from pressure drop calculations or empirically.
- Name the branches and the diffusers like in a conventional balancing. Begin the furthest downstream in the system and number up from there.

If the system has a quick response to changes, meaning that it takes few minutes to complete all system adjustments after each demand controlled throttle change, the following simplified procedure can be used:

- Open all manual dampers.
- Define the designed maximum and minimum airflow rate for each DCV damper and set the dampers to automatic mode. Read the opening grade.
- The trick is to find the Index damper, which is either the DCV damper with the highest opening grade or the manual damper with the lowest ratio between the measured airflow rates to the design airflow rate. It might be difficult to decide whether a DCV damper or a manual damper is the Index. One possible way is to adjust the pressure set point until the lowest manual damper ratio is approximately 1 (measured airflow rate ≈ design airflow rate). If the maximum opening grade of DCV damper is more than 85–80%, the DCV damper with maximum opening grade is the Index. If more than one DCV damper is fully open, the pressure set point is increased until all DCV dampers start to throttle. Otherwise the manual damper with the lowest ratio between the measured airflow rates to the design airflow rate is the Index.

The procedure then depends on which type of diffuser is the Index. If it is a CAV diffuser which is the index, the method is as following:

- Balance the diffusers with each other using the proportional method.
- Balance the branch dampers with each other – one branch damper and one diffuser should be and remain in a maximum open position (critical path).
- Reduce the pressure set point until you get the correct airflow rate at the index diffuser.
- Control the DCV units and write down the opening percentage in the VAV control form.

If it is a DCV that is the index, reduce first of all the pressure set point until the DCV Index diffuser gets the maximal airflow rate without throttling (maximum open position ≈ 80 % open). Then, balance the CAV diffusers with each other and branch dampers with each other. Both branch dampers must throttle in order to get the right airflow rate.

You have then found the energy optimal pressure set point, which is the lowest pressure set point which provides the right airflow rates according to the designed values.

- Complete the VAV control form.

If the system has a slow response to changes, meaning that it takes several minutes to complete the system adjustments after each throttle change, we recommend the following procedure:

- Open and block all the dampers, both CAV and DCV. The best is to require that all the DCV dampers have a programmed balancing procedure which opens all the dampers. The DCV units should be blocked at a maximum open position, *i.e.* around 80%. An alternative is to simulate a situation where the dampers are asked for more air than they can give, in order to get them in a maximum open position.

- Deactivate the automatic controls, or lock the dampers' position and fan speed in a different way.
- Carry out preliminary measurements. Fill up a VAV balancing form, state the design airflow rates, and both maximal and minimal airflow rate for the DCV diffusers. Calculate the ratio of the measured airflow rates to the design airflow rate for each diffuser. Find the Index diffuser (the one with the lowest ratio).

The procedure then depends on which type of diffuser is the Index. If it is a CAV diffuser which is the Index, the method is as following:

- Balance the diffusers with each other using the proportional method.
- Balance the branch dampers with each other – one branch damper and one diffuser should be and remain in a maximum open position (critical path).
- Reduce the pressure set point until you get the correct airflow rate at the index diffuser.
- Control the DCV units and write down the opening percentage in the VAV control form.

If it is a DCV that is the index, reduce first of all the pressure set point until the DCV index diffuser gets the maximal airflow rate without throttling (maximum open position). Then, balance the CAV diffusers with each other and branch dampers with each other. Both branch dampers must throttle in order to get the right airflow rate.

Finally, the actual maximum and minimum airflow rates values are programmed on each DCV unit. The automatic controls are activated and the DCV dampers are set in AUTO-mode. The VAV control form is filled in after the balancing, or during the functional check. The completed VAV control form should be included within the documentation of the ventilation system.

4.3 Balancing DCV systems with damper-optimized control

Balancing of DCV units in damper-optimized systems is very simple, and consists in specifying minimum and maximum design airflow rate for each DCV unit. This can be done either through the bus-system or by connecting a programming device directly on the DCV units. Various programming devices are used by the different suppliers. Balancing of a system with damper-optimized control can be combined with load testing (Chapter 5).

General checklist for balancing such a system:

- First, check that the damper motors, room sensors/ room regulators etc. have supply voltage and no connection error (polarity error).
- All the DCV units are programmed with V_{max} and V_{min}.
- If the DCV units do not give the expected response, check the polarity on the supply voltage.

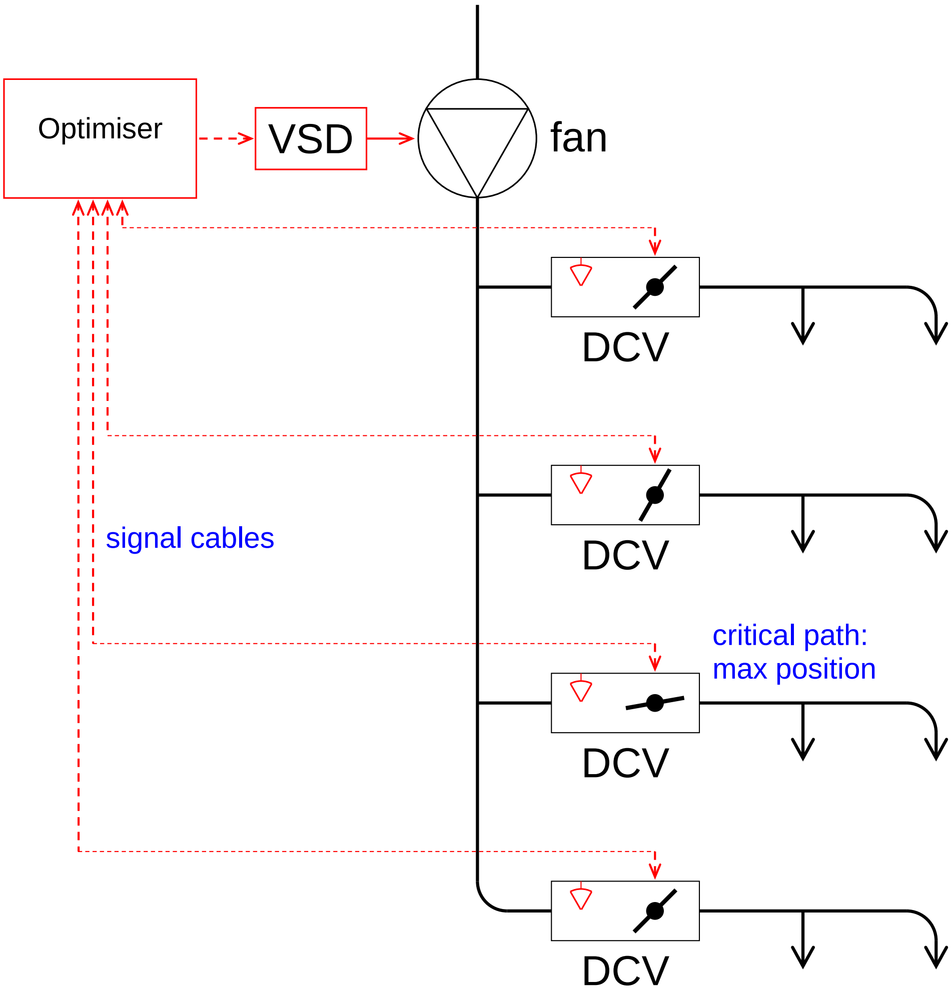


Figure 4.3 *Supply air section of a damper-optimized controlled DCV system.*

4.4 Balancing DCV systems with variable air supply diffusers

Balancing of a system with variable air supply diffusers is very simple, and consists in specifying minimum and maximum design airflow rate for each diffuser. This can be done either through the bus-system or by connecting a programming device directly on the DCV units. Various programming devices are used by the different suppliers. Balancing of a system with variable air supply diffusers can be combined with load testing (Chapter 5). On the exhaust section, DCV units are usually used which are connected to one or several of the variable air supply diffusers.

General checklist for balancing such a system:

- First, check that the variable air supply diffusers, room sensors/ room regulators etc. have supply voltage and no connection error (polarity error).
- All the diffusers are programmed with V_{max} and V_{min}.
- Program the DCV units on the exhaust section according to the corresponding diffusers.
- If the DCV units do not give the expected response, check the polarity on the supply voltage.

5 Load test and VAV control form

Recommendations in a nutshell:
We recommend an automated load test with minimum and maximum supplied airflow rate to all the rooms for maximum and reduced AHU load conditions.
If it is not possible to perform an automated load test because of the chosen components and or programming, we recommend checking all the rooms by measuring the airflow rate for maximum and minimum fan speed, for maximum and reduced system load. This control test should be documented with a completed VAV control form.
In buildings with many rooms with similar function, a random sampling according to the EN 12599 standard can replace the complete load test.

5.1 General

5.1.1 Simultaneity and presence

Simultaneity factor (*s*), often called diversity factor, corresponds to the ratio of the system's airflow rate to the design airflow rate for a CAV system. Presence (*p*) is the ratio of the number of persons present to the maximum number of persons present (design value) for a CAV system (*i.e.* around the percentage of room which have the maximum airflow rate). The corresponding equations are (Mysen, et al., 2005):

$$simultaneity,\ s = \frac{V_{AHU,\,VAV}}{V_{AHU,\,CAV}} = \frac{Sum\ V\ for\ all\ VAV\ units}{Sum\ V_{max}\ for\ all\ VAV\ units} \times 100\%$$

$$presence,\ p = \frac{Persons\ present}{Design\ of\ max\ nb\ of\ persons\ present} \cong \frac{Number\ of\ rooms\ with\ V_{max}}{Number\ of\ rooms} \times 100\%$$

The relationship between simultaneity and presence, for an AHU, is therefore:

$$s = \frac{p \cdot (\sum V_{max} - \sum V_{min}) - \sum V_{min}}{\sum V_{max}} \qquad (1)$$

$$p = \frac{(s \cdot \sum V_{max}) - \sum V_{min}}{\sum V_{max} - \sum V_{min}} \qquad (2)$$

How to determine the desired simultaneity?
If a ventilation system is designed for 100% simultaneity, all the DCV units must be able to deliver V_{max} simultaneously. However, DCV systems can be designed for a lower maximum simultaneity, for example, 65% simultaneity. This can be controlled during a functional check, by overriding the control in two different zones, where rooms in one zone are forced to V_{max}, while the rooms on the second zone are forced to V_{min}.

Equation (2) can be used to calculate how many rooms have to be forced to V_{max}. For example, if the AHU is sized for 65% simultaneity and the rooms are identical with V_{min}= 30 l/s and V_{max} = 100 m³/h, 50% of the rooms have to be forced to V_{max}, because:

$$p = \frac{s \cdot V_{max} - V_{min}}{V_{max} - V_{min}} = \frac{0{,}65 \cdot 100 - 30}{100 - 30} = 0{,}5 \quad ie.50\%$$

The remaining 50% of rooms are forced to V_{min}. After all the DCV units are checked, the control overriding is changed between V_{max} and V_{min} for both zones. At the end of the procedure, we have controlled that all the DCV units can supply V_{max} with 65% simultaneity.

A simpler approach, which avoids the calculation, is to force 50% of the rooms to V_{max} and read the total airflow rate in the AHU. If this differs from 65% simultaneity, you must adjust the number of rooms which are forced to V_{max} until the airflow rate in the AHU has the desired value.

5.1.2 The load tests Max-max-min and Min-min-max

Problems during operation occur most often for maximum or minimum load. Tests should therefore be carried out for these two operating situations. For each of these situations, it is necessary to consider each DCV unit and override the control signal from the room sensor (eg. temperature) in order to force the DCV unit to respectively max and min airflow rate, and document both fan speed drive in %, airflow rate, and opening grade. The Max-max-min load test is a control of max and min airflow rate for each DCV unit at maximum load. The Min-max-min test is a control of max and min airflow for each DCV unit rate at minimum load. This requires four control measurements per DCV unit. Such a control procedure is particularly relevant for DCV systems with pressure control and limited control possibilities from the BMS.

The opening grade tells us whether the DCV units work in a favorable range (40 to 80%) or not and if the pressure set point is reasonable.

A special inspection form is designed for this purpose (Figure 5.1). It is available in two editions: a written form (see appendix B) and Excel spreadsheets.

SINTEF

VAV-system kontrollskjema

Bygning ____________ Barometerstand ______ kPa
Anlegg ____________ Luftstrømstemp. ______ °C
Tegninger nr. ____________ Luftens tetthet ______ kg/m³
Utført av / dato ____________ Tillatt avvik ______ %

Rom/ sone	VAV-enhet ID		Prosjekterte luftmengder				TRINN 1. Max samtidighet i bygget													TRINN 2: Min luftmengde i bygget											
	Tilluft	Avtrekk	Tilluft		Avtrekk		Inn-stilling *	Max tilluft lokalt			Max avtrekk lokalt			Min tilluft lokalt			Min avtrekk lokalt			Max tilluft lokalt			Max avtrekk lokalt			Min tilluft lokalt			Min avtrekk lokalt		
			Vmax [m³/h]	Vmin [m³/h]	Vmax [m³/h]	Vmin [m³/h]		Vmax [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmax [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmin [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmin [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmax [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmax [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmin [m³/h]	Vmålt/ Vpros	Posisj. [%]	Vmin [m³/h]	Vmålt/ Vpros	Posisj. [%]

* Kort beskrivelse av de ulike innstillingene for max samtidighet ved testing av ulike ventilerte soner, gjelder både tilluft og avtrekk
#1
#2
#3

Figure 5.1 Recommended form for VAV control measurement.

5.2 Procedure for the load test

5.2.1 Max-max-min

The Max-max-min load test is a functional test of the DCV system at the maximum airflow rate (*ie.* maximum simultaneity) that the AHU is designed for.

Work steps :
a) Force control the DCV units in one part of the building to V_{max}, so that the AHU's airflow rate increases to the design value, while the DCV units in the rest of the building are forced to V_{min}.
b) In the part of the building where the rooms are forced to V_{max}, go from room to room and control if the airflow rate through the DCV units (supply and exhaust) is equal to V_{max}. These measurements are filled in the pink columns («Local max supply/exhaust»).
c) Next, repeat the control of the same rooms, but instead, force the DCV units to V_{min} one room at a time, and control that the airflow rate falls to V_{min}. These measurements are completed in the blue columns («Local min supply/exhaust»).
d) Now repeat steps (a) to (c) to control the rest of the rooms, *i.e.* rooms on the side of the building that was not forced to V_{max}. For example, in a 10-story building with a common AHU, you can switch to force control the bottom 5 floors and the top 5 floors to V_{max}.

5.2.2 Min-min-max

The Min-min-max load test is a functional test of the DCV system at minimum airflow rate (*i.e.* minimum simultaneity) that the ventilation system is designed for.

Work steps :
• Force control all DCV units in the building to V_{min}.
• Move from room to room and control if the airflow rate through the DCV units (supply and exhaust) is equal to V_{min}. These measurements are completed in the blue columns («Local min supply/exhaust»).
• Then, repeat the control with DCV units to V_{max} in one room at a time, and control that the airflow rate reaches V_{max}. This procedure tests the function for example for overtime work, and is a hard test for some DCV system to manage. These measurements are filled in the pink columns («Local max supply/exhaust»).

Why test V_{min}?
Many may wonder why it is necessary to test V_{min}. It is important for the following reasons:
• We test V_{min} to check that V_{min} is within the operating range of the DCV units.
• The test with V_{min} in all rooms except for one room with V_{max}, confirms that the persons in this room actually get the air they need, for example when working overtime.
• We test V_{min} to confirm that a low SFP value is achieved outside of normal operation time (night/weekend).
• We test V_{min} to check that the DCV system is well-functioning at minimum load.

5.2.3 How to force all the DCV units in the building to V_{max} / V_{min}?

- A good alternative is to override the room control (change the set point on the temperature sensor/CO_2 sensor). Often, only the temperature signal has to be changed which then overrides the CO_2 signal. This can often be done centrally via the BMS. It is important to remember to set the set point back to the initial value after the test!

- DCV controllers may be able to override all the connected DCV units. This is fast and efficient, but experience shows that this function is usually not available if it has not been asked for during the offer/purchasing stage.

5.2.4 How to force a single room for testing of V_{max}/V_{min}?

- Option 1: For buildings with BMS, the DCV units can be forced to V_{max} by changing the set point for room temperature to for example 10 °C or CO_2 to 100 ppm. Likewise, it is possible to the force the airflow rate to V_{min} by changing the set point of CO_2 to 10.000 ppm and/or room temperature to 30 °C. The advantage of this option is that it also checks the integrity of the room sensor signal cable.
- Option 2: Otherwise, you can use dedicated software to override DCV units one by one. This is especially time saving when all the DCV units' bus signals are combined on the same board.
- Option 3: Use the dedicated handheld programming device to set V_{min} to V_{max} or the opposite. This option is not preferable, since one can forget to set V_{min} or V_{max} back.

5.2.5 How to measure the airflow rate?

There are several suitable methods of airflow rate measurement related to the documentation of maximum/minimum load testing:

- Option 1: Read the airflow rate which is recorded with the DCV units' own measuring station (readout via BMS, etc.). This method is fast but requires that the DCV unit's measuring station is accurate. This method is recommended for newer models of DCV units with favorable location (in compliance with the vendor's requirements in terms of minimum straight duct both before and after the DCV unit). The method is unsure for older models which were individually calibrated at the factory
- Option 2: Use the common Nordic methods (Johansson and Svensson, 2007), for example by measuring the airflow directly with a cone, or with a pressure sensor and k-factor over the diffuser, or a Pitot tube in the branch duct.

5.3 Spot-checking during the load test

Experience has shown that the contractor should control absolutely **all** the DCV units with all the above combinations of overriding, as part of commissioning, in order to guarantee a flawless system upon handover. This should be required explicitly as a contractual requirement.

In the case of third-party witnessing during commissioning, and inspections after handover, one normally resorts to spot-checking (*i.e.* to control only a limited number of DCV units, which are randomly selected), because it is too time-consuming to repeat the above process. The standards EN 12599 Annex C (2012) and EN 14134 (2004) provide guidelines for the number of samples, depending on the total number of DCV units. Below are two levels of sampling:

High number of samples, category A: $n = 1{,}6 \cdot N^{0{,}4}$

Low number of samples, category C: $n = 3{,}16 \cdot N^{0{,}5}$

where:

n number of DCV units which are spot-checked

N total number of DCV units in the system (sum of supply and exhaust)

5.3.1 Improved spot-checking procedure

The disadvantage of the above sampling methods is that they are not very well statistically founded. A simpler method, called «*zero acceptance number sampling*», involves testing at least 28 random DCV units, irrespective of the total number of units in the building. This guarantees that less than 10% of the DCV units in the building are faulty (or less than 1% units on average). This method is based on «sampling without replacement» (hypergeometric distribution). The procedure is as follows:

The third-party randomly selects 28 DCV units for testing. If no faults are found, then the test is complete.

If a fault was found among any of the 28 units, then the contractor is ordered to correct and re-commission any faults in the DCV system. Upon completion of this, the third-party randomly selects a 28 different DCV units for testing (not including the first group of 28 units). If no faults are found, then the test is complete.

If a fault was found among the new selection, then the contractor is given a second chance to correct all the faults and re-commission the system. Upon completion of this, the third-party must witness the testing of all the DCV units in the entire system.

5.4 Automated load test

It has proven to be very difficult or impossible in practice (either technically or time-wise) to override DCV units in a load test. One should therefore strive to automate the load test completely by programming it in the control panel or in the BMS. This has several advantages: it can be a complete test (not spot-checking) with all combinations of overriding, it reduces costs significantly, and can be repeated as often as needed (once a year during normal operation, or after changes in the system).

6 Troubleshooting and corrective measures

Recommendations in a nutshell:
One should expect that the handover procedure will reveal deviations from the initial requirements and there must be time to improve and re-test the system. Further on, new deviations will occur during the operation phase. It is important that the automatic controls and the BMS make it easy to detect deviations. It is also important that the system's regulating components are available for inspection and replacement.

6.1 Deviations at handover and during operation phase

Knowing which typical problems may occur makes it easier to troubleshoot and correct the ventilation system. Errors on new systems can often be blamed on design, mounting and component failures. After some time, «typical» operating problems can happen.

6.2 Too high pressure set point for fan control

An important purpose of balancing is to find the energy optimal pressure set point, which is the lowest pressure set point which can provide the right airflow rate at maximum load. In many cases, the pressure set point is too high. This implies that the fans build up an unnecessary high pressure at all time, and that all the DCV dampers throttle. Such a system will always «speed up» and «brake» at the same time, wasting fan energy and generating increased noise. One characteristic of such a system is that all the DCV dampers always throttle. This can be controlled with the BMS. If all the DCV dampers throttle when the load is high, the pressure set point should be reduced.

6.3 Pressure sensor – Choice, location, number, and scheme to detect and solve errors

The pressure sensor which controls the fan speed drive is of critical importance in a pressure controlled DCV system. The sensor must follow the changes at room level and contribute to a corresponding change at AHU level. A sensor which does not record the changes correctly and automatic controls which do not respond in a proper way are responsible for a wrong airflow rate (poor indoor climate), risk for energy losses and risk for unstable cyclic variation between the supply and the exhaust.

Many choose to have only *one* pressure sensor. The later can suffer from reduced performances because of:

- mounting which induces mechanical strain
- operating conditions leading to an abnormally high pressure, such as a combination of high fan speed and low airflow rates (can happen during commissioning, cyclic variation, signal failures etc.)
- dust and soiling, especially if the sensor is on the exhaust section
- electrical incidents (overvoltage/undervoltage etc.)
- natural wearing/aging

After some time, there is a risk that the pressure sensor's signal deviates too much, or becomes unstable. This causes the system to not work in an optimal way, and it can be difficult to pinpoint the underlying cause. All DCV systems should have a scheme concerning how such deviations should be noticed and solved before the consequences become too important. One measure is to have two pressure sensors to control the fan speed. The fan speed can then be controlled according to an average value and an alarm can be set if the difference between the smallest and largest value is too important, or if the deviation varies.

The sensor should be placed in a favorable way, on a location with stable pressure. It should have a sufficient precision and stability over time. The sensor should be placed as far in the system as possible, and should also capture all the pressure variations which result from the DCV dampers. Placing the sensor as far as possible in the system also allows for reduced pressure set point. This induces a lower fan energy use during partial load.

If one is unsure about the placement of the sensor, one measure is to carry out control measurements of dynamic and static pressure at the location of the sensor for different operation conditions.

Ventilation systems with long ducts and large duct pressure drop can be particularly challenging for constant pressure control, because the pressure variations resulting from demand control are relatively small compared to the total pressure drop of the system. It makes it even more challenging to find a favorable location of the sensor which captures the changes with sufficient precision. For such systems, the control should be divided between a pressure-controlled fan speed, controlled by a pressure sensor in the main canal, and pressure controlled branch dampers, which are motorized control dampers receiving a 0–10 V signal from the pressure regulator for the zone, as shown on Figure 1.2.

6.4 Placement of room DCV damper and branch DCV damper

Room dampers and branch dampers measure and control from the specified minimum to the maximum airflow rate in accordance to the airflow rate requirements given by the room sensor or the pressure sensor. This assumes that the airflow rate and the duct pressure are within the product's measuring range, and that the damper is suitably located in relation to airflow obstacles. Many DCV dampers measure and regulate to a «wrong» airflow rate because they are located too close to the duct junctions. The distance to a junction upstream or downstream of the DCV damper depends on type of product and the velocity ratio between the main channel and the branch. If no specification is given, the distance to the junction should be at least of 5 duct diameters, as shown on Figure 6.1.

Figure 6.1 A short distance between the upstream branch and the DCV damper can cause the DCV damper to measure a wrong airflow rate.

6.5 Room or branch DCV dampers measure a low or zero airflow rate

Many DCV dampers have a dynamic pressure sensor. A small part of the supply airflow rate is collected via a tube and goes through a dynamic pressure sensor that measures velocity. Particles in the ventilation air can soil the tube and the pressure sensor, which affects the air velocity measurement. This is particularly a problem with DCV dampers in the exhaust section of the ventilation system, and causes that the DCV dampers measure a too low airflow rate. Recent DCV dampers are designed in a way that they are more robust with respect to dust exposure, and a measure is to switch to a new and more robust solution. It is also possible to use DCV dampers with static pressure sensors which are particularly robust in respect to soiling.

If you suspect that this problem may be occurring, it is possible, for some products, to clean the tube and the pressure sensor by blowing compressed air in the opposite direction of the ventilation flow. This must be done in accordance with the damper and sensor suppliers' recommendations.

There should be inspection hatches at each DCV damper in order to control and clean the damper. Inspection hatches are particularly important in the exhaust duct, since that is where problems with soiling are the most important.

6.6 Functionality of the branch DCV damper for minimum airflow rate during operation time

In a school, the ventilation system typically starts a few hours before the classrooms are used. All the room DCV dampers then attempt to maintain the minimum airflow rate in each classroom. The corresponding branch DCV damper must be able to adjust the airflow rate well below the sum of the minimum for each classroom. Otherwise, if the airflow rate goes below the measuring range, the branch DCV dampers will record that the airflow is equal to zero and open the damper to the maximum open position, allowing the airflow rate to increase far above the requirements. With a little delay, the DCV damper then records a too high airflow rate, and begins to throttle again. This causes an unstable cyclic variation in the system. The supply and exhaust sections are usually independent of each other, so the cyclic variation is often different for the supply and exhaust air. This can cause a switching between overpressure/under pressure in the rooms. In schools, we have experienced that an unstable system in the morning works correctly during the schooldays, when the classrooms are in use, but become unstable again at the end of the schooldays. One corrective measure is to use a smaller DCV damper.

6.7 Placement of combined CO_2 – temperature sensors

The correct placement of sensors depends on conditions such as:

- ventilation strategy at room level (mixing or displacement)
- air diffuser location
- contaminant sources/heat sources location and characteristics
- temperature conditions
- room geometry
- sensor type

Usually, a combined CO_2 and temperature sensor is used. These are mounted vertically with enough free space around the sensor. They must not be in direct sunlight, or be affected by radiation from a heater in the room. They should also be located away from the door that is open during normal operation. If they are near a closed door, this can be a good location because it can be placed together with the light switch, and there is little risk for covering. Note that the sensor must be at a good distance from light switches with dimmer, because these emit significant heat.

If the duct of the pressure sensor is located in a conduit, there can be measuring errors due to the difference of pressure and possible airflow in the conduit.

The room height at which the sensor should be placed depends on the ventilation principle used. Mixing ventilation should in principle provide a constant pollution concentration in the room. This means that the sensor can be placed anywhere in the room or at the exhaust, as long as the sensor is not too close to the contaminant sources or the to the supply diffuser. But even if one aims for mixing ventilation, concentration gradients in the room and dead zones will often occur in practice. Therefore, the sensor should be placed most centrally in the occupied zone as possible. A prerequisite to place the sensor in the exhaust is that the conditions at the exhaust should be representative of the condition in room. For example, a low ventilation rate and presence of internal heat loads can result in a higher temperature at the sensor than in the room. In this case, DCV based on temperature control cannot work.

When displacement ventilation is used, cool air with low velocity is supplied close to the floor. For a displacement ventilation strategy controlled by a combined temperature and CO_2 sensor, the sensor should be placed in the breathing zone (around 1,1 m above the floor), so that one gets good ventilation efficiency up to and in the breathing zone.

6.8 Presence detector

Presence detectors should be placed so that that there is no visual obstacle between the sensor and the work station. The detector must cover the whole room. If the detector controls the lighting, it should be sufficiently fast and sensitive. Use of combined PIR and ultrasound detector is a possible solution in a room with problematic light control.

6.9 Polarity error

Mysterious errors, which occur in certain cases, may be due to polarity error in the connection between the damper’s motor and the 24 V transformer. Although there are 24 V AC, it should be connected as DC. The reason for this is that G0 is used as a reference for the 0–10 V signal.

On suspicion of polarity error, *all the connections should be controlled from the transformer to the damper's motor*. Such control is time consuming. This can be avoided by using solutions which eliminate the possibility for incorrect connection, or by following the installation closely on the installation site.

6.10 Other signal errors

Too long wires with insufficient cross-section may result in signal failures. A cross-section of 0.5 mm^2 is usually sufficient.

6.11 DCV dampers and room control – typical errors, causes and consequences

Table 6.1 shows common errors which can occur with DCV dampers and room control. The table also includes errors which may occur during operation. The troubleshooting begins by detecting an undesirable consequence.

Table 6.1 Typical errors with DCV dampers.

Error nb.	Component	Error	Cause	Type	Consequence
1	Temp Sensor	Deviation	Wear and tear	Incipient	Measured zone temperature deviates from actual zone temperature.
2	Temp Sensor	Locked	Wear and tear	Critical	Measured zone temperature is constant, and deviates from actual zone temperature.
3	Airflow rate Sensor	Locked	Wear and tear	Critical	Does not measure the change in supplied airflow rate, and can therefore not ensure a correct airflow rate in relation to the varying demand.
4	Airflow rate Sensor	Locked on Min or Max	Wear and tear	Critical	Does not measure the change in supplied airflow rate, and can therefore not ensure a correct airflow rate in relation to the varying demand.
5	Airflow rate Sensor	Deviation	Wear and tear	Incipient	The actual supplied airflow rate is different than the airflow rate asked for by the controller.
6	Damper	Blocked	Wear and tear	Critical	When the damper is blocked, the airflow rate is constant (static pressure control)
7	Damper	Hanging	Wear and tear	Incipient	When the damper is hanging, the supplied airflow rate lays always behind the airflow rate asked for by the controller.
8	DCV Terminal	Under capacity	Design	Critical	Does not manage to provide the required airflow rate.
9	DCV Terminal	Measures an airflow rate equal to 0 (airflow rate too low to be measured)	Component	Critical	Unstable operation. Supplies more air than necessary in short periods.

7 References

Boylestad, R. 2010. *Introductory circuit analysis*. 12th ed. Upper Saddle River, N.J.: Prentice Hall.

Chauvin Arnoux. 2003. *CA8334 User manual*. Chauvin Arnoux.

Commission, C.E. 2010. *2008 Building energy efficiency standards for residential and nonresidential buildings*. Sacramento, Calif.: California Energy Commission.

Direktoratet for arbeidstilsynet. 2012. *Veiledning om klima og luftkvalitet på arbeidsplassen: veiledning fra Arbeidstilsynet*. Trondheim: Arbeidstilsynet.

EN 14134. 2004. *Ventilasjon i bygninger – Ytelsesprøving og installasjonskontroll av ventilasjonssystemer i boliger*. Oslo: Standard Norge

EN 15251. 2007. *Inneklimaparametere for dimensjonering og vurdering av bygningers energiytelse inkludert inneluftkvalitet, termisk miljø, belysning og akustikk*. Oslo: Standard Norge.

Grini, C. and T. Wigenstad. 2011. *Leco. Behovstilpasset ventilasjon : Hvordan får man alle brikkene på plass?* Oslo: SINTEF Byggforsk.

Johansson, P. and A. Svensson. 2007. *Anvisning 16-7 Metoder for måling av luftmengder i ventilasjonsanlegg*. Formas.

Klima- og forurensningsdirektoratet. 2013. *Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes: Annual report 2011*. TA 3035.

Klæboe, M.W. og T.W. Herrmann. 2011. *Optimalisering og videreutvikling av behovstilpassede ventilasjonsanlegg med trykkstyring som reguleringsprinsipp*. Aalborg: Aalborg Universitet.

Kommunal- og regionaldepartementet. 2010. *Forskrift om tekniske krav til byggverk (byggteknisk forskrift, TEK10): av 26. mars 2010 nr. 489*. Ikrafttredelsesdato: 1 juli 2010. Oslo: Norsk byggtjenestes forlag.

Maripuu, M.-L. 2009. *Demand controlled Ventilation (DCV) systems in commercial buildings: functional requirements on systems and components*. Göteborg: School of Electrical and Computer Engineering, Chalmers tekniska högskola.

Mysen, M. 2012. *Bruksprofil i skoler – som grunnlag for å vurdere energisparepotensialet med behovsstyrt ventilasjon*. Oslo: SINTEF Byggforsk.

Mysen, M., S. Berntsen, P. Nafstad and P.G. Schild. 2005. «Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools». *Energy and Buildings*, 37: 1234–1240.

Mysen, M. and P.G. Schild. 2012. «How to purchase Demand Controlled Ventilation with energy optimal functionality?». *Healthy Buildings 2012 : 10th International Conference 8-12 July 2012 Brisbane, Australia*. Queensland University of Technology.

Mysen, M., P.G. Schild and F. Drangsholt. 2010. «Robustness and True Performance of Demand Controlled Ventilation in Educational Buildings – Review and Needs for Future Development». *31st Air Infiltration and Ventilation Centre Conference 2010 : (AIVC 2010) : low energy and sustainable ventilation technologies for green buildings : Seoul, South Korea, 26-28 October 2010*. Seoul: International Network for Information on Ventilation and Energy Performance.

Novakovic, V., S.O. Hanssen, J.V. Thue, I. Wangensteen and F.O. Gjerstad. 2007. *Enøk i bygninger*. Oslo: Gyldendal.

NS-EN 12599. 2012. *Ventilasjon i bygninger – Prøvingsprosedyrer og målemetode for overtakelse av ventilasjons- og luftkondisjoneringsanlegg*. Oslo: Standard Norge.

NS 3031. 2007. *Beregning av bygningers energiytelse – Metode og data*. Oslo: Standard Norge.

Schild, P.G. and M. Mysen. 2009. *Recommendations on Specific Fan Power and System Efficiency*. International Energy Agency, Energy conservation in buildings and community systems programme.

Smiths, F., M. Kilingland, A.F. Lånke, I. Andresen, K. Elvebakk, F. Holthe, M. Monsen Ragnøy and M. Holmesland. 2013. *Energiregler 2015 : forslag til endringer i TEK for nybygg*. Utredning for Direktoratet for byggkvalitet. Rambøll.

Stadheim, L.A. 2013. *SFP ved behovsstyring – Retningslinjer for krav og kontroll*. Oslo: Høgskolen i Oslo og Akershus.

Wildi, T.W. 2006. *Electrical machines, drives, and power systems*. 6th ed. Upper Saddle River, N.J.: Prentice Hall.

8 Terminology

Variable Supply Air Diffuser (VSAD). Control principle where the fan speed is controlled such that one VAV damper is in a maximum open position and where the VAV dampers are integrated in the air diffusers.

DCV (Demand Controlled Ventilation). Ventilation systems whose airflow rate is controlled automatically according to an actual demand at room level.

Bus-system. Generic term for computer network management, control and surveillance systems. Bus systems are network systems in which all devices are connected to the same communication line (bus). Messages on the bus are going to all the devices, but only the addressed device captures and processes the message.

CAV-system. (Constant Air Volume) Ventilation systems which operate with constant airflow rate over the whole operation phase of the air handling unit.

DCV damper. Motor-damper with automatic controls for throttling and measurement of either airflow rate or pressure drop. The DCV damper receives a signal from sensors. This signal Is converted to an airflow rate demand towards which the DCV damper regulates to.

Pressure controlled DCV. Control principle where the fan speed is controlled to maintain a constant pressure at the location of a pressure sensor in the main duct.

PLC (Programmable Logic Controller). Most common type of substation for continuous control of the system via bus. It is in practice a computer with a specialized PLC programming language, for example to optimize the dampers' position and fan speed, and that can have set points which are change via the BMS.

Ppm. (parts per million). Measure of the volume of a gas relative to the volume of air.

Control-damper. Fixed control damper.

BMS (Building Management System). PC with software (or virtual web solution) which communicates with the control center (s) to give the operation personnel the opportunity to control the technical systems.

SFP (Specific Fan Power). Ratio of the electrical power required to operate a fan, and the volume of air moved by the fan. Expressed in [kW/(m^3/s)].

Damper-optimized DCV. Control principle where the fan speed is controlled such that one VAV damper is in a maximum open position

Pressure-optimized DCV. Control principle where the fan speed is controlled to maintain an optimal pressure at the location of a pressure sensor in the main duct.

TVOC (Total Volatile Organic Compounds). Total concentration of VOC or total amount of volatile organic compounds. Measurement of TVOC in indoor environments can provide indications on air quality.

VAV damper. Motor damper which controls the airflow rate according to a signal using automatic controls and and throttling.

VAV-system. (Variable Air Volume). Designates all ventilation systems whose airflow rate can vary.

VOC (Volatile Organic Compounds). Volatile organic compounds found in the air (mixture of different gases). VOCs in an indoor air quality context include emissions from building materials, equipment, furnishings, furniture, textiles, detergents, food and beverage, paints, people, animals, cosmetics, microorganisms etc. Measurement of VOCs in indoor environments can provide indications on air quality.

VSD (Variable Speed Drive). or VFD (Variable Frequency Drive). Component of the fan motor which is used for controlling the fan speed.

Terminology in appendix C:

Balancing: manual adjustment of dampers and diffusers in a ventilation system so that all parts of the systems receive the design airflow rate during normal operation.

Diffuser: supply air and exhaust organs.

Typical diffuser: Diffuser which provides uniform air distribution, is easy to measure and provide good measuring accuracy. Reference diffuser is often used as typical diffuser.

Sub-branch: Duct with a group of diffusers which are all operated by the same damper, for example. Sub-branch AA in Fig. 1.

Branch: duct with multiple sub-branches that are all operated by the same damper, eg. branch A.

Section: bigger or smaller section of a ventilation system which is operated by the same damper, eg. Section A or B on Fig1.

Reference diffuser or reference branch (R): the diffuser (AA 1) which is the furthest on a branch or the branch (AA) in a subsystem which is firthest from the fan.

Index diffuser or index branch (I): the diffuser/branch in a subsystem which has the lowest percentage of the designed value when all dampers are open, ie the valve (AA 2), respectively. branch (AA), which has the lowest ratio ("unfavorable diffuser/branch")

RRatio (f): the ratio between measured and designed air supply (airflow rate, air velocity or pressure) for a diffuser or branch. The ratio can also be expressed in percentage of designed airflow rate

$$f = \frac{\textit{measured value}}{\textit{design value}}$$

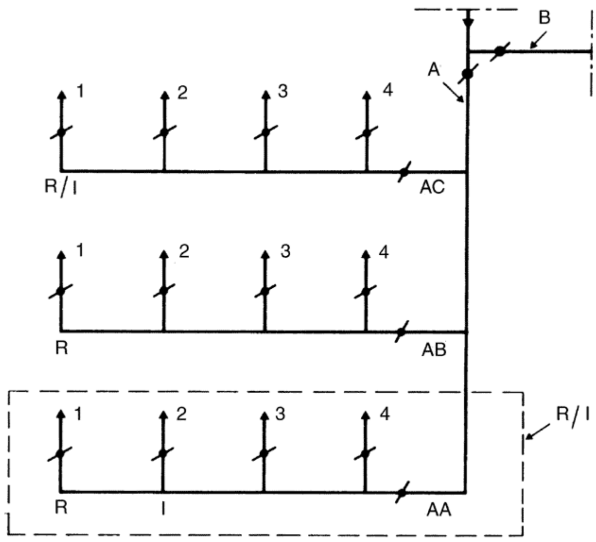
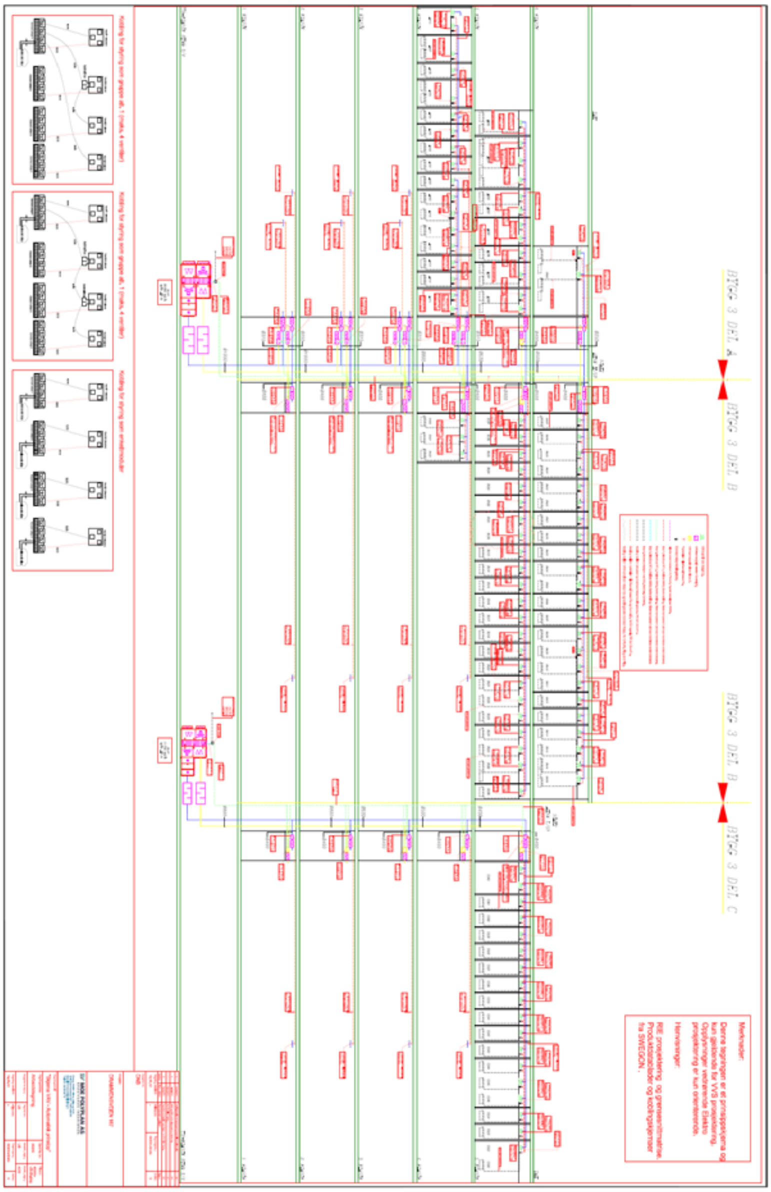


Fig. 1
Example on the supply section of a ventilation system

Appendix A: Automatic controls diagram



Appendix B: VAV Control form

SINTEF

VAV-kontrollskjema

Bygning ______ Barometerstand ______ kPa
Anlegg ______ Luftstrømstemp. ______ °C
Tegninger nr. ______ Luftens tetthet ______ kg/m^3
Utført av / dato Tillatt avvik %

Trykk-set-punkt før innregulering [Pa]:	SFP kontroll ved maksimal samtidighet [3600*kW/m^3/h]:	SFP kontroll ved minimum luftmengde [3600*kW/m^3/h]:
Trykk-set-punkt etter innregulering [Pa]:	Vifteeffekt tilluft [kW]: Vifteeffekt avtrekk [kW]: Største luftmengde [m^3/h]:	Vifteeffekt tilluft [kW]: Vifteeffekt avtrekk [kW]: Største luftmengde [m^3/h]:

Rom/ sone	VAV-enhet ID		Prosjekterte luftmengder				TRINN 1. Max samtidighet i bygget													TRINN 2: Min luftmengde i bygget												
			Tilluft		Avtrekk		Inn-	Max tilluft lokalt			Max avtrekk lokalt			Min tilluft lokalt			Min avtrekk lokalt			Max tilluft lokalt			Max avtrekk lokalt			Min tilluft lokalt			Min avtrekk lokalt		
	Tilluft	Avtrekk	Vmax [m^3/h]	Vmin [m^3/h]	Vmax [m^3/h]	Vmin [m^3/h]	stilling *	Vmax [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmax [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmin [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmin [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmax [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmax [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmin [m^3/h]	Vmålt/ Vprosj	Posisj. [%]	Vmin [m^3/h]	Vmålt/ Vprosj	Posisj. [%]
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	
									-			-			-			-			-			-			-			-	

*** Kort beskrivelse av hvilke rom, eller deler av bygningen, der VAV-enhetene er tvangsstyrt til Vmax, og hvordan du har tvangsstyrt (f.eks. endre temperatursettpunkt)**

Appendix C: Balancing using the proportional method

1 General

11 CONTENT

This appendix deals with the usual procedure when balancing a ventilation system using the proportional method. Emphasis is given on carefully describing this systematic procedure. Common tasks which have to be carried out before the measurements on the systems are described in VENT 64.102 Preparations for balancing.

12 BACKGROUND

There are various methods for balancing of ventilation systems, such as proportional, pre-setting, and SOL method, see VENT 64.100. The proportional method is probably the most common method. Most supply air and exhaust systems, regardless of type and size, can be adjusted totally or partially with this method.

2 Balancing procedure

21 INTRODUCTION

Balancing using the proportional method consists in controlling the dampers and diffusers in the system such that that all the diffusers supply the same percentage of the design airflow rate. The procedure follows a "step-after-step method" in which each operation is dependent on the preceding step. Finally, when the fans (total airflow rate) are adjusted, all the diffusers in the system supply the design airflow rates.

211 Possibilities for modified method

A person who has learned the principle of the method and has experience with balancing in practice will be able to use the method in some modified form on all systems where balancing is conducted. Beginners should not walk away from the procedure that is initially planned, because "shortcuts" can easily lead to time consuming rebalancing.

22 BENEFITS

221 Method for all types of system

The proportional method can be used for all types of ventilation systems. This appendix mainly gives a schematic description of the working method. However, there are great possibilities for personal initiative, which makes the work interesting, but also responsible.

222 Parts of the system can be balanced independently

Balancing can be divided into several independent operations.
A group of diffusers can be balanced independently of the conditions in the other parts of the building and on different days for large systems. Balancing of parts of the system can be performed even if the whole system is not assembled. In this case, a mobile fan is used that is connected to the appropriate subsection/branch. The method can also provide an early warning if a diffuser or a section of the system will not reach the designed airflow rate.

223 Relative measurements

It is not necessary to measure the airflow rates when balancing the system. Balancing can be based on relative measurements such as air velocity or pressure.

224 Reduced throttling

A damper or a diffuser which has been balanced once does not need to be balanced more times, which saves time. Throttling of the system is minimized. The noise level can thus be kept to a minimum.

225 Combination with other methods

In practice it will be advantageous to combine the presetting method and the proportional method. Groups of diffuser may eg. Be calculated and preset while groups are balanced with each other with the proportional method. In many cases, the proportional method may be the only actual balancing method.

3 Theoretical background

31 PRINCIPLE

The proportional method is based on the principle that the ratio between the airflow rates in two branch channels remains constant even if the airflow rate in the main channel leading to this junction varies. This principle means that the airflow rate in both branch channels will decrease by 20% if the total airflow rate is reduced by 20%, by regulating the damper in the main channel, see Fig. 31.The same conditions apply to all diffusers and branches in the system.

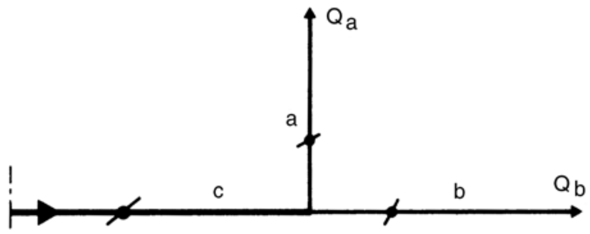


Fig. 31

The ratio between q_a and q_b is constant and independent of a variation of the airflow rate in c, as long as the resistance (damper position) in a and b does not change.

This principle is used in a systematic way for balancing, where the airflow rates of the individual diffusers and branches are successively adjusted in order to obtain the same ratio to the design airflow rate. The proportional principle applies only to the parts of the system which are downstream of the fan which is adjusted.

32 THEORY

321 Relationship between airflow rate and pressure

The proportional method assumes that there is a certain relationship (quadratic) between the airflow rate changes and pressure changes in the ductwork.

$$\left[\frac{q_1}{q_2}\right]^2 = \frac{p_1}{p_2}$$

where

q is the airflow rate

p is the pressure

322 Pressure drop

The total pressure loss in a ductwork consists partly of friction resistance in the ducts and partly of the pressure drop due to individual resistance such as bends, branches etc. The pressure drop across a ponctual element of the ductwork (also called point losses) can be expressed as:

$$\Delta p_{stat} = \xi \cdot p_{dyn}$$

where

ξ is the point losses coefficient

p_{dyn} is dynamic pressure :

$$p_{dyn} = \frac{\rho}{2} \cdot v^2$$

ρ is the air density

v is the velocity

The point losses coefficient is constant within a broad velocity range. In some parts of the ductwork, for example T-junctions, there is however not an entirely clear relationship between airflow rate and changes in pressure, which may be a problem for large airflow changes in the system. The resistance changes within the typical velocity range according to the square of velocity. The friction coefficient varies with the Raynolds number (Re). At low Re values, changes happen quickly, but at higher (normal) Re values, the coefficient is constant. The relationship between airflow arte and pressure drop allows basing balancing on relative measurements.

323 Validity range

For large airflow changes, the relationship between friction resistance in branch ducts, for example in a and b in Fig. 31, can lead to undesirable deviations in the airflow rate relationship between both junctions. However, calculations show that the variations in airflow rate ratio that occurs in ordinary ventilation systems is negligible (<2%) when the airflow rate varies in the range of 50% to 150% of design value. For the error to be minimal, the method should be used only when the airflow rate in the system is within ± 50% of the designed value.

324 Recommended inbalance lower than ± 30 %
In order to prevent unfavourable flow conditions and inadvertent pressure losses, it is recommended that the imbalance in the section of the system to be balanced to not be greater than ± 30%. If necessary, the branch ducts should therefore be roughly controlled to be within ± 30%, by closing some of the branch ducts. These branch dampers must be opened again before the balancing of the branches starts. It is important to plan balancing such that one starts in the right section of the system. The working procedure which is intended for a system should be followed as closely as possible.

33 METHOD DESCRIPTION
The proportional method is illustrated on a simple duct with four diffusers (fig. 33). When balancing a group of diffusers, the reference diffuser is always the one which is the furthest downstream of the fan. Basically, the idea during balancing is that this diffuser has the lowest airflow rate ratio compared to the design aiflow rate.

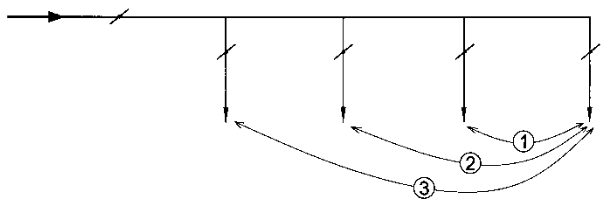


Fig. 33
The figure illustrates the sequence of operations necessary to balance a group of diffusers.

If another diffuser in the group has a lower ratio (index diffuser), the reference diffuser is adjusted so that the ratio becomes approximately equal to the index diffuser's ratio (±allowed deviation). Throttling of the reference diffuser must be adjusted such that the damper of the index diffuser is in a maximum open position after balancing. The balancing method consists in balancing the other diffusers towards the reference diffuser by adjusting the damper of the diffusers such that the airflow rate ratio between measured and design value is identical for each diffuser. The sequence of operations when balancing is illustrated on Fig. 33. The same method is used when balancing sub-branches, branches, and the main ducts.

34 TOLERANCE WHEN BALANCING
It would be impractical and very costly to perform a balancing diffuser and branches until exactly the same percentage of design airflow is obtained for all diffusers and branches in the system. The project documents should contain realistic tolerances for both secondary and main airflow rates. Unless otherwise specified, the tolerance including measurement uncertainty should not exceed ± 15% for diffusers and ± 10% for the main airflow rate.

4 Balancing procedure – general method

The procedure for balancing a fully assembled ventilation system is described below. The description is based the system illustrated on Fig. 4. Note that balancing can be divided into independent operations, see section 222. This advantage is used frequently in large buildings where balancing must following the building construction progress. In such cases, a mobile fan is connected to the subsection/junction which is fully assembled and ready for balancing.

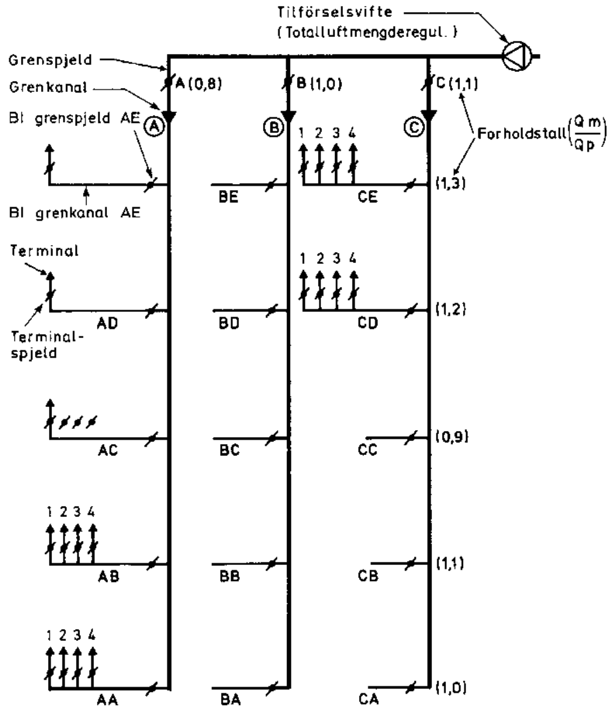


Fig. 4
Principle diagram for balancing of a ventilation system

41 PREREQUISITES

Before the balancing of the ventilation system can begin (usingthe proportional method or other methods), preparatory work should be carried out, the system should be controlled and commissioned, and preliminary measurements made, see VENT 64.102 Preparations for balancing. It is assumed that all dampers and diffusers in the system of Fig. 4 are open.

42 WHERE SHOULD THE BALANCING START?

Based on the results of the preliminary measurements, a program for the balancing procedure should be set up.

421 Which system should be balanced first?

In principle, the system which has the biggest pressure drop over the diffuser should be balanced first, because it is less influenced by the pressure variations which often occur between the rooms. In systems with low pressure, the exhaust section of the system is therefore often balanced first. Exhaust terminal devices often have a higher pressure drop than supply diffusers.

422 Branches

Balancing should normally start at the branch or subbsection of the system which has the highest percentage of the projected value, *ie.* the branch which has the highest ratio. On Fig. 4, branch C has the highest ratio (f = 1.1, *ie.* 10% more airflow than planned for the junction). If the percentage of one branch is higher than 30% of the projected value, the branch damper should throttle to reduce the airflow rate under that level. The idea is to start balancing and push some of the excess air from the parts of the system where there is the highest ratio ("most" air) to the sections which have the least air.

423 Diffusers on the branch with the highest ratio

The next task consists to find which of the sub branches on branch C which has the highest ratop. On Fig. 4, the subbranch CF holds the highest ratio, and the balancing should begin with this one. The first thing to do is to balance the diffusers on this subbranch such that they have the same ratio.

424 Other subbranches

After that the diffusers on the subbranch CE have been balanced to supply the same percentage of designed airflow rate, one should find which of the subbranches of branch C which has the next highest ratio. After the diffusers have been balanced there, one should continue the balancing procedure in a systematic way, by balancing the diffusers on the subbranch which has the highest ratio. The procedure for balancing of the whole system presented on Fig.4 after the proportional method is described in details below.

43 WORK PROCEDURE

The balancing procedure is divided into independent operations, but after a fixed main pattern (see Fig.4). The work steps during balancing should follow the description given in table 43.

Table 43
Work procedure for balancing

Work proceudre
1. Balancing of the diffusers on each subbranch
2. Balancing of the subbranches
3. Balancing of the branches
4. Adjustment of the main airflow rate

When balancing, all the diffusers on each subbranch should be treated as an independent group. Likewise, subbranches and branches should be considered like diffusers on the branch or on the main duct and balanced between each other as if they were a group of diffusers.

431 Diffusers
All the diffusers on a section of the system, for example branch C should be balanced before moving the dampers of the subbranches CA, CB, and so on in this section of the system (see point 5).

432 Subbranches
After all the diffusers on the same subbranch of the branch C are balanced, the next task consists in balancing the subbranches CA, CB, etc. to the same ratio. The branch damper C should not be moved (see point 6). The diffusers and subbranches on the remaining branches or system section (B and A) should be balanced according to the same procedure.

433 Branches
The branches A, B and C should be balanced at the end. All the diffusers in the system should have the same ratio after this operation (see point 7).

434 Total airflow rate
A the end, the main airflow rate should be adjusted such that all the diffusers have a ratio of 1, ie. deliver the designed airflow rates ± allowed deviation (see point 8).

435 Control of reference diffuser/branch
During balancing, any adjustment of the dampers or diffusers will change the ratio in the others (nearby) branches or diffusers. It is therefore necessary to control the reference diffuser/ branch frequently.

5 Balancing of diffusers

51 INDEX AND REFERENCE DIFFUSER

The first task is to find out which diffuser on the subbranch has the lowest percentage of designed airflow rate, ie. the index diffuser (from preliminary measurements). This is often the last diffuser of the subbranch. If this is not the case, the reference diffuser is adjusted to approximately the same percentage (ratio) as the index diffuser (± allowed deviation).

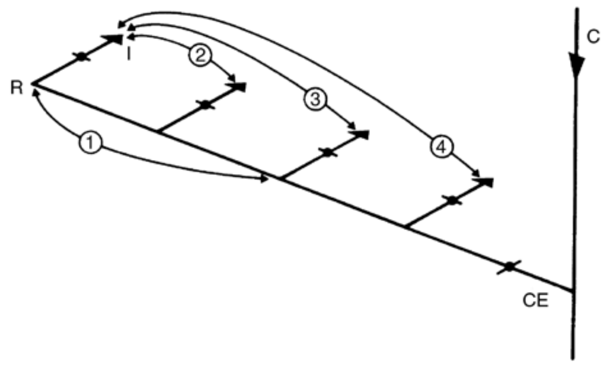


Fig. 51
The figure shows the four work steps which are usually necessary for the balancing of the diffusers on this subbranch,. R = reference diffuser, I = index diffuser.

Figur 51 illustrates the index and reference diffusers and the work steps to balance the subbranch CE. The diffuser which is the furthest in the branch (CE-1, reference diffuser) should always be used as reference. The other diffusers in the group (CE-2-3-4) should be compared/balanced towards the reference. This procedure should always be used (also when balancing branches), since the proportionality only works downstream.

Table 52
Procedure for balancing diffusers on a subbranch

1	Measure the airflow rate from diffuser CE-3 (index diffuser) and diffuser CE-1 (reference diffuser). Calculate the ratio for each of the diffusers.
2	Compare the ratio for CE-1 and CE-3.
3	Regulate the diffuser CE-1, ie. throttle the reference diffuser because this one basically has the highest percentage of design airflow rate than CE-3 which is the most "unfavourable".
4	Measure, compare and regulate until the ratio for CE-1 and CE-3 is almost the same (± allowed deviation)*). When the reference diffuser har received the lavest ratio, the other diffusers can be balanced according to CE-1.
5	Measure the airflow rate from the diffuser CE-2. Calculate the ratio.
6	Compare the ratio for CE-2 and CE-1.
7	If the ratio for these diffusers is outside of the allowed range, the diffuser CE-2 should throttle such that the tolerance required is fulfilled. Be aware that the ratio for the reference diffuser (CE-1) will raise when throttiling the other diffusers. Calculate therefore the new ratio for CE-1 after each adjustment.
8	Control that CE-3 har the same ratio as CE-1, (see point. 4). An adjustment may not be necessary.
9	Regulate CE-4 til to the same ratio as CE-1. Do not move the dampers of CE-2 and CE-3**). The diffusers on the branch CE have now the same ratio. Lock and note the diffusers.
10	Balance the diffusers on each of the other subbranch (CA, CB, CC and CD) on branch C with the help of the same procedure. Begin with the subbranch which has the next highest percentage of designed airflow rate (CD). The subbranch dampers should remain in a maximum open position.

*) *Throttling of the reference diffuser should be adapted such that the damper of the index diffuser saty in a maximum open position after balancing. In practice, CE-1 should therefore often be set to a new higher ratio than CE-3.*

**) *While balancing, one should be aware that the reference diffuser CE-1 changes a little by throttling the diffusers which are located far away from the reference diffuser, and that diffusers that has already been balanced should not be adjusted again, as these will rise to the same ratio as the reference diffuser when throttling of the diffusers upstream occurs.*

Appendix D: Methods for measuring specific fan power

Source: Stadheim, Leif Arne; HiOA 2013

8.1 Power measurement in AC circuits

To calculate the specific fan power in a tri phase balanced circuit, one does not have to carry out a star or triangle wiring. If one has access to the voltage, current and power factor for the circuit, then it is possible to use the following formula (Boylestad, 2007):

$$P = U * I * \cos\phi * \sqrt{3}$$

P = active power [W]

U = voltage [V]

I = current [A]

$\cos\phi$ = power factor []

8.2 Methods for measuring the specific fan power

The wattmeter that is mentioned in the wattmeter method is a monophasic wattmeter. When one uses this method, it is not necessary carry out a star or triangle wiring, balanced or unbalanced. There are also three-phase wattmeters (commonly called "power analyzers") that measure the total active power in one go with one instrument.

8.2.1 Two-wattmeter method

The two watt meter method can be used for a three phase circuit, such as a motor. The wattmeters are wired as shown in Figure 1 (Wildi, 2006). The sum of the absolute-values of the two wattmeters, $|P_1| + |P_2|$, gives the delivered power. The two-wattmeter method is suitable both for balanced and unbalanced circuit.

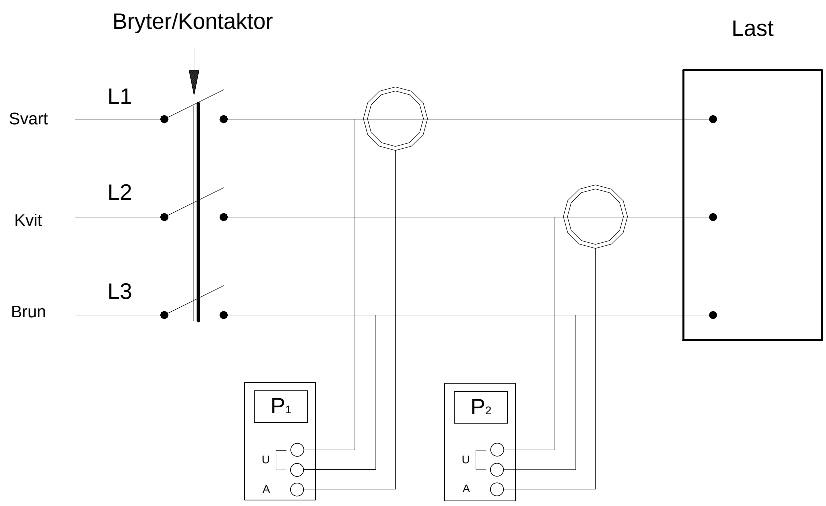


Figure 1. Two wattmeter method.

8.2.2 Power measurement using three-phase power analyzers

A three-phase analyzer can measure the voltage and current for all three phases at the same time. A simple measurement can then give the SFP. The wiring diagram is shown on Figure 2 (Chauvin Arnoux, 2003). These are by far the most practical way of measuring three-phase fan motors.

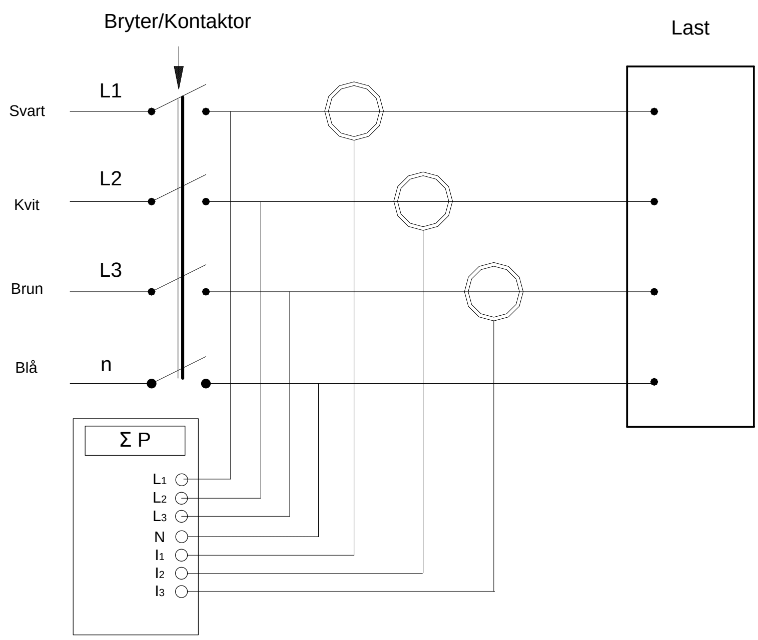


Figure 2. The figure displays the wiring of an analyser to a three phase circuit. N-leiaren vert tilkopla der den er til stades (stipla linje).

8.2.3Three wattmeter method

The measurement of SFP is carried out as shown on Figure 3. The sum of the three wattmeters, $P_1 + P_2 + P_3$, gives the delivered power. The three wattmeter method is suitable both for balanced and unbalanced circuit.

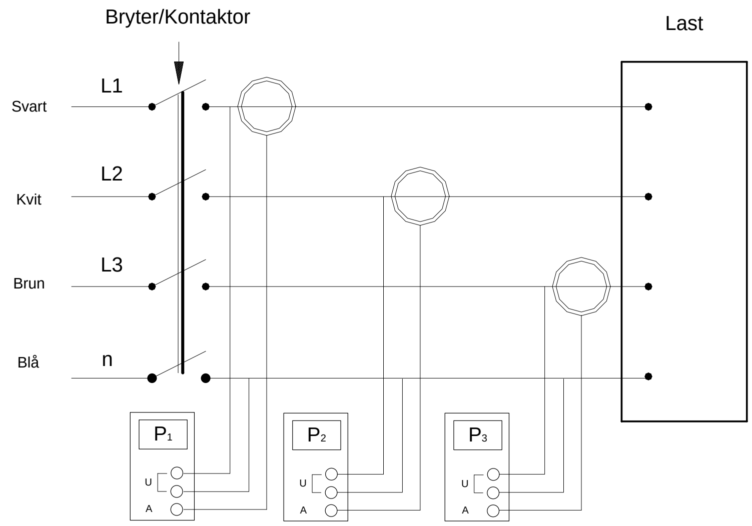


Figure 3. SFP measurement in a TN circuit with three wattmeters

DEMAND-CONTROLLED VENTILATION –REQUIREMENTS AND COMMISSIONING

GUIDEBOOK ON WELL-FUNCTIONING AND ENRGY-OPTIMAL DCV

Most of the content of this guidebook results from the Norwegian research and development project «reDuCeVentilation» – Reduced energy use in Educational buildings with robust Demand Controlled Ventilation. The aim of the project was to develop solutions to provide good indoor climate with minimal energy use in educational buildings. The presented solutions are also suitable for office buildings.

The purpose of this guidebook is to help building owners to acquire well-functioning demand-controlled ventilation by applying the guidebook's recommendations, as well as proper commissioning. Contractors and property managers can use the guidebook to improve the quality of new systems, while facility managers can use it for troubleshooting and maintenance of existing ventilation systems.

The project was led by SINTEF Building and Infrastructure. It started in 2009 and finished in 2013. It was supported by the Norwegian research council, VKE, Skanska, Undervisningbygg Oslo KF, Optosense, Micro Matic Norge, Swegon og TROX Auranor Norge.

SINTEF Academic Press