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The Impact of Conservation Voltage Reduction on Energy Consumption and Total Harmonic Distortion

A Comparative Study of Five Conservation Voltage Reduction Units

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Abstract

In this work the impact of five different systems for conservation voltage reduction (CVR) on energy savings and total harmonic distortion (THD) are measured and compared. For this purpose, a load network is set up under laboratory conditions and electrical power and total harmonic distortion (THD) are measured in front and behind of the CVR unit. Each load is measured separately, in order to investigate the influence of the voltage reduction on the useful work performed.

For a defined load network with 10 % voltage reduction, a reduction of power consumption of up to 5.9 % can be measured. The savings are almost exclusively achieved by the load groups of halogen spotlights and fluorescent tubes. Due to the voltage reduction a significant reduction of illuminance can be measured for those two load groups. For switching mode power supplies (SMPS), motors with frequency converter or LED lighting, no significant savings can be measured. The influence on the THD of the current and the voltage is rather small.

In summary, it can be shown that the use of CVR units can reduce the power consumption of certain load groups. This energy savings lead to a reduction of the useful work performed by the respective load. A detailed analysis of the composition of the electricity demand of a site is therefore recommended before installing a CVR unit. In this context, planned measures to replace existing lighting technology should also be taken into account.

Keywords: Voltage reduction, energy savings, efficiency, total harmonic distortion

Note: The measurements have been carried out in 2019 at the laboratory of SWK E² in Krefeld.

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1. Introduction

Experiments and research on conservation voltage reduction (CVR) are ongoing for more than 35 years now [1], [2]. CVR can be applied at the network level (see [3]) or at the consumer level. In this work, the application of CVR in industrial and commercial sites is considered. A large number of systems are available on the market, which are designed to save energy by reducing the voltage. Savings of 13 % and higher can be found in the specifications of manufacturers or sales and marketing documents (e.g. [4]). Often, the savings measured by the manufacturer's own measurement methods range between 3 and 7 %, depending on the load structure of the application (e.g. [5]). For companies, the use of CVR units therefore appears to be a simple way of achieving the company's energy policy goals with minimum effort.

Due to the first law of thermodynamics, energy can't be created or destroyed but only converted into another form of energy. During the conversion, heat losses can occur that cannot be used anymore. Here, the useful part of energy (called exergy) is converted to unusable energy (called anergy). Nevertheless, energy as a whole remains constant. [6]

Considering the fundamentals of thermodynamic, energy savings due to voltage reduction can have three major reasons:

1. the efficiency of the connected loads increases,
2. the useful work performed by the connected load is reduced,
3. losses are reduced.

VDE-AR-E 2055-1:2009-10 [7] presents a calculation principle for energy savings through voltage reduction. The calculation is based on the fact that, according to DIN EN 60038:2012-04, the supply voltage may deviate by 10 % from the nominal supply voltage $U_N = 400$ V/230 V [8]. This implies a maximum voltage reduction down to 360 V/207 V and a maximum rise up to 440 V/253 V. The calculation method is essentially based on the different influence of the voltage on the energy consumption of different loads. A distinction is made between voltage-dependent loads α, power constant loads β and energy constant loads

γ. In the case of voltage-dependent loads, the energy consumption is directly dependent on the voltage U. If the voltage is lowered, the power consumption and also the output power of the load is reduced. Power constant loads, on the other hand, are constant in their power consumption. A voltage reduction leads to an increase of the current I. For energy-constants loads, the amount of energy consumed remains constant. Power P can be expressed as the quotient of work W and time t. If the voltage and therefore the power consumption is reduced, the operating time of the load is extended, until the same amount of energy has been used. The energy consumption of the respective load groups (voltage-dependent, power-constant and energy-constant) can be calculated using the following equations. [7], [8]

$$W_\alpha = \alpha \cdot \frac{U^2 \cdot (1-u)^2}{z} \cdot \cos\phi \cdot t \tag{1}$$

$$W_\beta = \beta \cdot \frac{U^2}{z} \cdot \cos\phi \cdot t \tag{2}$$

$$W_\gamma = \gamma \cdot \frac{U^2}{z} \cdot \cos\phi \cdot t \tag{3}$$

By identifying the shares of the respective loads (α, β, γ), the energy savings due to voltage reduction can be calculated [7]. The sum of shares of the loads must always be 1.

$$\alpha + \beta + \gamma = 1 \tag{4}$$

According to the mentioned first law of thermodynamics, it can be seen, that for power constant and energy constant loads, no savings in energy consumption will be achieved. For voltage-dependent loads the savings $s_{\alpha=1}$ can be calculated by equation (5), but voltage reduction will also lead to a reduction of the useful work of the load.

$$s_{\alpha=1} = \frac{U_0^2 - U_S^2}{U_0^2} \tag{5}$$

For an initial voltage of $U_0 = 230$ V and a reduction down to $U_s = 207$ V savings of 19 % can be achieved, if all loads are voltage-dependent. In reality, the shares of voltage-dependent loads steadily decrease (see [7]), since more electronic loads, like switching mode power supplies (SMPS), frequency converters (FC) or LED and electronic ballasts in lighting systems replace older and less efficient technologies. The γ-values given in VDE-AR-E 2055-1: 2009-10 have not been adjusted during the last decade and therefor can be considered as too high in many cases. The savings calculated according to the standard are therefore often higher than the actual achievable savings. For this reason, a revision of the γ–values is recommended.

Only a few studies are available in the literature that independently investigate the influence of voltage reduction and harmonic distortions on energy savings. In 1987 Chen et al. [1] were one of the first to present a simulation of voltage reduction on energy consumption of distribution systems. According to Wilson [2], electrical energy is saved through reduced distribution system losses, due to voltage reduction. In addition, the lifespan of some loads, like incandescent lamps and hot water heater elements, increase. Wilson considers, when reducing the voltage, for some loads unacceptable operating conditions can result from under voltage. Sundermann [9] evaluated the data from a one-year field trial of a commercially available CVR unit. The system was switched on for one day and switched off the following day. Overall, a reduction in annual energy consumption of between 0.16 % and 1.2 % was calculated. Kampezidou and Wiegmann [10] analysed the implementation of a CVR in a test building. Based on the measurements, they calculated savings of about 1.5 % for a voltage reduction of 5 %. The authors conclude, that due to increasing shares of loads with power electronics regulations (constant power loads), the application of CVRs will get more and more difficult [10].

In an experimental study in 2016, Singaravelan and Kowsalya [11] investigated the effect of voltage reduction on conventional household appliances. In table 1 some of their measured loads and the reduction of power consumption in percent by reducing the voltage from 230 V to 200 V are presented. According to equation (5), the maximum saving can be 24.4 %.

Table 1: Power reduction for conventional household appliances, according to [11]

Appliances	Power for 230V [W]	Power for 200V [W]	Power reduction [%]
PC Desktop	55.00	55.00	0.00
Iron	951.09	730.58	23.20
Television	121.83	121.83	0.00
Air Conditioner	800.00	635.16	20.60
Water Pump	371.99	323.47	13.00
Lighting (LED)	240.00	240.00	0.00

It can be seen, that typical type α consumer like an iron, lead to a high reduction of power or energy consumption. Probably the same result can be achieved by reducing the iron's temperature. For appliances with switching mode power supplies or electronic ballasts, no reduction can be measured. Motors seems to be mixed-type loads. The lighting investigated appears to be LED lighting, but was not further specified by the authors. [11]

For field tests it is very difficult to predict the behaviour of loads over a long period of time with sufficient accuracy and therefore, the measurement and proof of savings are often not reliable [12]. The supposed proof of savings is often provided by switching between saving mode and bypass at regular intervals. However, as the behaviour of the loads is often not taken into account, the reliability is limited. In addition, it is almost impossible to measure the useful power output. For example, the measured savings can result in a reduction in illuminance or reduced volumetric flows and thus lead to a reduction in the amount of useful energy. [13]

Since it is very complex and expensive to measure the useful energy of all loads in a field test, a load network was set up under laboratory conditions to measure all relevant electrical parameters in front and behind the CVR unit and the useful energy of each load connected the the CVR unit separately. In the following chapter, the measurement setup is described in detail.

2. Measurement Setup

Within the scope of the experimental investigation, five CVR units from different manufacturers are tested under laboratory conditions. The measurements are reproducible and the measurement data and the derived savings are documented. The aim is to ensure that the input power, the internal consumption of the CVR units and the useful work performed by the load can be measured separately. In addition, a symmetrical load and a minimum load of at least 10 % of the nominal current are ensured for each phase.

The experimental setup is directly connected to the university's electricity grid via a 32 A connection. On the input side, two power analysers measure the active power of the three phases $P_{1,in}$, $P_{2,in}$, $P_{3,in}$ as well as their voltages $U_{1,in}$, $U_{2,in}$, $U_{3,in}$ and currents $I_{1,in}$, $I_{2,in}$, $I_{3,in}$, the harmonic distortions of the voltage $THD_{U_1,in}$, $THD_{U_2,in}$, $THD_{U_3,in}$ and current $THD_{I_1,in}$, $THD_{I_2,in}$, $THD_{I_3,in}$, as well as the power factor. The sum of the active power consumption of all phases is defined as total power consumption $P_{tot,in}$. The equivalent values are measured with a power analyser on the output side of the CVR unit (index out instead of in). By comparing the active power on the input and the output side of the CVR unit, the internal consumption can be calculated. Behind the power analyser on the output side, five groups of loads are connected. The experimental setup is shown in Figure 1.

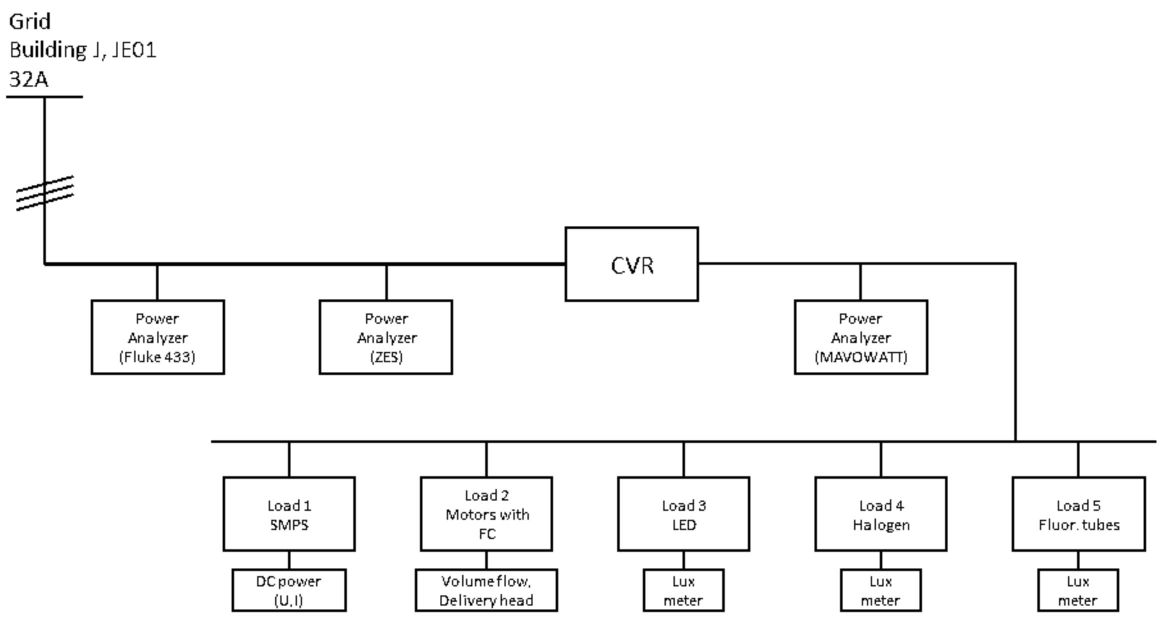

Figure 1: Experimental setup of the CVR unit, the loads and measurement equipment in the laboratory

Identical loads are combined into load groups (LG) and measured together. LG1 consists of six DC switching mode power supplies (SMPS) with resistive loads on the output side. The useful work of the SMPS are calculated from the DC voltage U_{DC} and current I_{DC} measurements. When selecting the SMPS, particular emphasis was given to an unsteady current curve and a high THD_I.

LG2 consists of two AC motors with frequency converters (FC) that drive two centrifugal pumps, which pump water from a tank via pipes through an absorption chilling machine (ACM) back into the tank. During the experiments, the ACM is turned off and only used, because it is part of an existing setup in the laboratory. The volume flow rate $\dot{V}$ in m^3/h is measured via the Programmable Logic Controller (PLC) of the laboratory. The delivery head H in m is calculated from the pressure difference between the suction and pressure side and the rotational speed of the pump, and is given via an infrared interface to a smartphone application of the pump manufacturer.

LG3 consists of ten LED tubes and fifteen LED spot lights. The illuminance E_v in lux is measured with a lux-meter on a tripod. Due to the strong influence of the positioning of the tripod on the measurement value, no absolute values, but the change in value between bypass and saving mode are evaluated.

LG4 consists of two halogen spot lights and LG5 of a mix of different fluorescent tubes with different nominal power, socket size and ballast. Measurements of the lighting are carried out in a darkroom in the laboratory and the individual measurements are shielded from each other by black plates. The influence of the neighbouring light measurements was less than 2 % of the measured illuminance in all three cases. Each lighting group (LG 3-5) is connected to a different phase, so that an approximately symmetrical load distribution is ensured during network measurement. The data of the loads investigated in this work are given in Table 2.

Table 2: Specifications of the measured load groups

Load Group	Description	Specifications of the load	P_{total} [kW]
LG1	SMPS	6 x DC Switching power supply Komerci oHG, PS3010N, 10 A, 30 V	1.8
LG2	Motors with FC	2 x Grundfos TPE(D) Series 2000, MGE100LC2-FF215-G3, 3x380-480 V, 6.2-5 A, 3 kW, 0-120 Hz	6.0
LG3	LED	10 x Aura Light UltiLED Pro Long Life G8, 3000 K, Tridonic LC 38 W 500-700 mA flexC lp ADV, 26 W; 15 x Molto Luce Schienenstrahler, 637-00 102049050, 27 W	0.7
LG4	Halogen	2 X Candy light 500, 500 W	1.0
LG5	Fluor. tubes	11 x Spectrum WOJ21118, 36 W; 2 x T8 Sylvania Luxline plus 840, 58 W; 4 x T5 Sylvania Luxline plus 840, 49 W	0.7

Figure 2 gives an impression of the experimental setup of the loads in the laboratory. The measurements were carried out in three steps:

1. Measurement of the internal energy consumption of the CVR units by varying the active power consumption of the SMPS between $P_{tot,out} = 0 - 1750$ W and measuring the total power consumption on the input side for bypass and saving mode.

2. Separate measurement of each load group.
3. Measurement of all load groups together in a network.

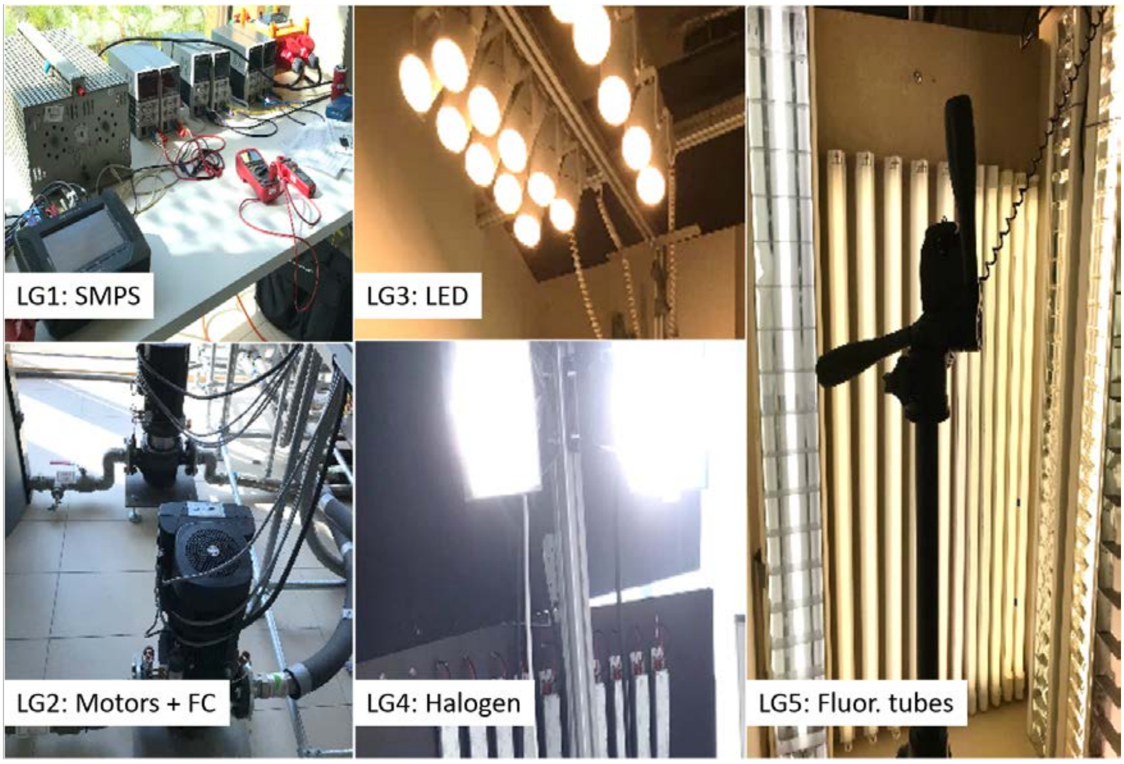

Figure 2: Experimental setup of the load groups in the laboratory

According to confidentiality, the five tested CVR units will be named A, B, C, D and E. The corresponding manufacturer or model description are therefore not mentioned in this paper. The voltage reduction of each unit can be taken from Table 3. For some units U_s can be set in the laboratory. For others, the value is specified by the installed components and cannot be changed. All CVR units are treated as a black box. The functionality and the structure are not considered but only the measurable effects on the power consumption.

3. Results

Figure 3 shows the internal consumption of the different CVR units in Watt. It is measured by the difference between the power on the input and on the output side $(P_{tot,in} - P_{tot,out})$. The internal consumption varies between 190 and 4 W. The internal consumption of unit A remains approximately constant with increasing load. In the load-free state, an increased consumption can be measured. Unit B has a slightly increasing internal consumption with increasing load and for unit C, the internal consumption in saving mode drops down to 3.9 W with increasing load. Consumption in bypass remains constant for all units. For large sites, the internal consumption can be seen as neglectable low. For domestic applications it seems difficult to compensate the internal consumption by savings.

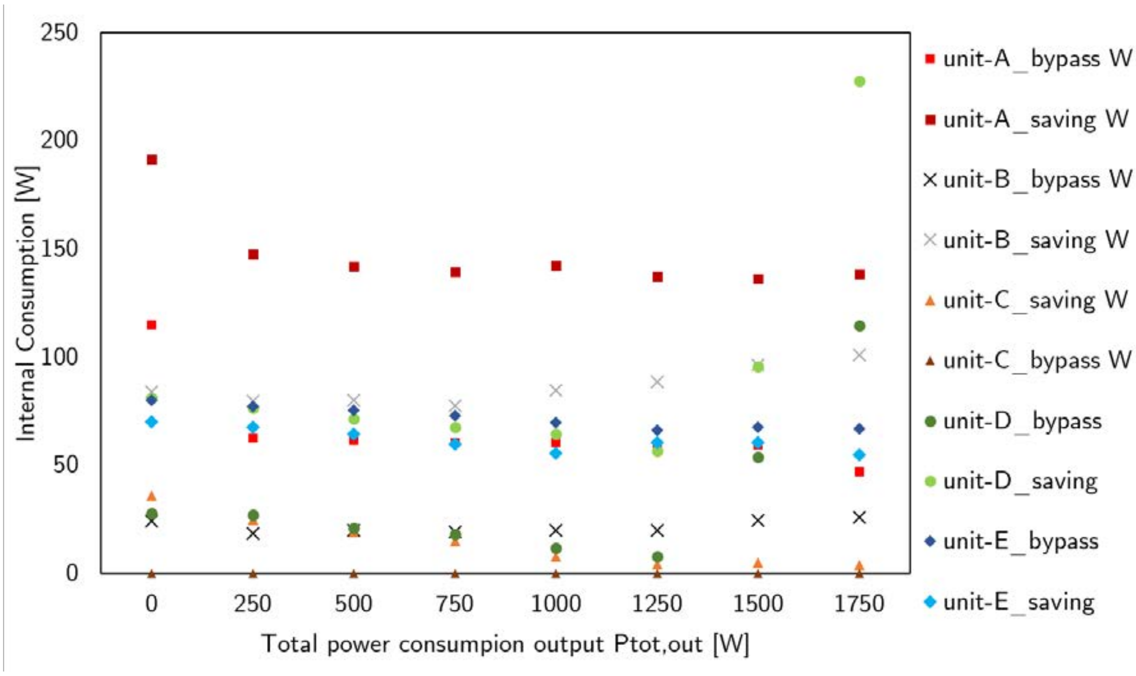

Figure 3: Internal consumption for CVR units A, B, C, D and E in bypass and saving mode with increasing total power consumption $P_{tot,out}$

In the appendix A selected measurement data of all CVR units are shown. The presented measurement data include the active power on the input and output side for each load group, as well as all loads together in a network. By comparing the total power in bypass and saving mode, a conclusion about the potential savings of the different consumers can be made. In addition, specific indicators are measured for each load to quantify the influence of CVR on the performance of the load. For all SMPS, the DC voltage and current are measured to calculate the DC output power. Each of the two motors with FC drives a centrifugal pump, whose flow rate and delivery head are measured. For each lighting group (LG3-5) the illuminance was measured separately.

When comparing the power consumption on the input side (including internal consumption) during network measurement, it can be seen that the power consumption for system B is greater in saving mode than in bypass mode. For systems A, C, D and E, a reduction in power consumption can be measured. When considering the power measurement of the individual loads on the output side, no reduction in power consumption can be seen the LG1 (SMPS), LG2 (motors with FC) and LG3 (LED lighting) for all CVR units. The only exception is unit C with motors as load. For all these three LGs (1, 2 and 3) no significant reduction on the output can be seen, except for unit C where a reduction of 0.83 to 1.44 % can be measured. For LG4 and LG5 switching into saving mode leads to a reduction in power consumption for each CVR unit. Power consumption for halogen spot lights decreases on the output side (without internal consumption) between 8.8 and 14.2 %. The illuminance decreases even more between 17.0 and 27.1 %. For fluorescent tubes, the reduction of power consumption (- 3.2 to - 5.6 %) and illuminance (- 4.0 to - 7.3) is less high.

All values have to be set in relation to the amount of voltage reduction ΔU of the CVR unit and can therefore not be compared directly. To quantify the energy savings, a $CVR_P - factor$ is defined in equation (6) according to [12] as the ratio of power consumption reduction ΔP_{tot} over the voltage reduction ΔU.

$$CVR_P = \frac{\Delta P_{tot}[\%]}{\Delta U[\%]} \tag{6}$$

The results of the five CVR units can be related to the respective value of the voltage reduction and are shown in Table 3. $\Delta P_{tot,in}$ and $\Delta P_{tot,out}$ in percent are the measured reductions of power consumption in the network measurement on the input and the output side.

The relative reduction is calculated as deviation from the bypass value. Based on the measured voltages on the output side in the bypass and saving mode, the relative voltage reduction in percent can be determined using the same procedure. Now the $CVR_W - factor$ can be calculated according to equation (6) for the input and the output side. With an assumed voltage reduction of 10 %, a reduction of the power consumption $\Delta P_{\Delta U=10\%,in}$ between + 0.2 (B) and - 2.89 % (C) can be calculated, for the input side. In case of CVR unit B, the internal consumption overcompensates the savings. On the load side of the CVR units (output), a reduction of power consumption $\Delta P_{\Delta U=10\%,out}$ between - 0.63 (A) and - 6.34% (C) is calculated. It has to be mentioned, that for unit C a larger reduction of the useful work of the load of LG1, 2 and 3 are measured (see appendix A).

Table 3: Total power and voltage reduction and CVR factor for all CVR units A, B, C, D and E

Unit	$\Delta P_{tot,in}$	$\Delta P_{tot,out}$	ΔU	$CVR_{P,in}$	$CVR_{P,out}$	$\Delta P_{\Delta U=10\%,in}$	$\Delta P_{\Delta U=10\%,out}$	$S_{\alpha=1}$
A	- 0.9	- 0.7	10.9	0.09	0.06	- 0.86	- 0.63	- 19.8
B	+ 0.1	- 1.0	7.5	0.02	0.15	+ 0.20	- 1.45	- 13.3
C	- 1.2	- 2.6	6.2	0.29	0.63	- 2.89	- 6.34	- 11.4
D	- 0.3	- 1.0	6.5	0.05	0.17	- 0.54	- 1.68	- 12.0
E	- 1.1	- 1.1	9.2	0.12	0.12	+ 1.17	+ 1.24	- 17.5

To compare the development of the useful work performed by the individual load group, a second CVR-factor for the change of the useful work of the load in relation to the voltage reduction is defined in equation (7). The useful work is understood as the measured output values of the load, like DC power for LG1, flow rate for LG2 or Illuminance for LG3-5.

$$CVR_W = \frac{\Delta W_{use}[\%]}{\Delta U[\%]} \tag{7}$$

For each load group, it is now possible to compare the change in power consumption and the change in useful work performed by the load. The mean value is then calculated for the measured values of the five different CVR units. The results are shown in Figure 4.

In addition to the reduction of power consumption, the effects on THD of the current ΔTHD_I and the voltage ΔTHD_U were also investigated. As can be seen in Figure 1, harmonic distortions are measured in front (input) and behind (output) the CVR unit. It can be seen, that on the grid side both, THD_I (- 0.1 to 4.3 %) and THD_U (- 0.0 to 0.9 %), decreased. On the load side, THD_I decreases between 0.2 and 4.2 % while THD_U stays approximately constant for the units A,B, D and E and increased for unit C. Overall, it

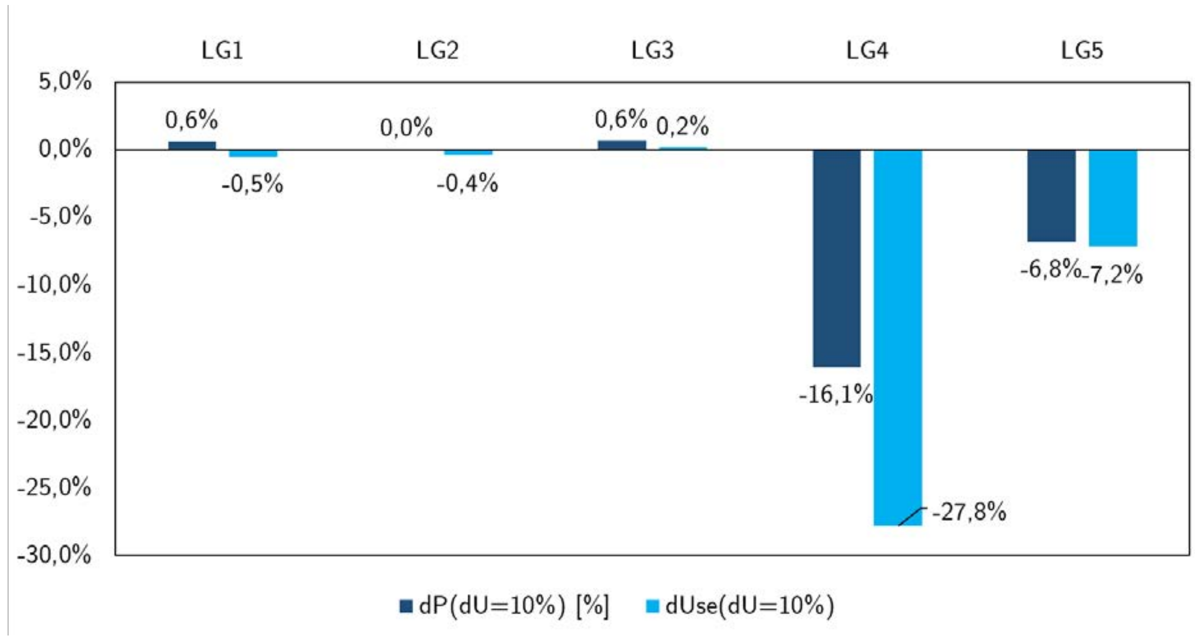

Figure 4: Change in power consumption and useful work of the load groups 1 to 5 for a voltage reduction of 10 %

can be stated that the influence of the devices on THD is comparatively small. The largest influences can be measured for device C. The changes in THD of the network measurements are shown in Table 4.

Table 4: Change in total harmonic distortion of the current ΔTHD_I [%] and the voltage ΔTHD_U [%] for different CVR units A, B, C, D and E

	Input (grid side)		output (load side)	
Unit	ΔTHD_I	ΔTHD_U	ΔTHD_I	ΔTHD_U
A	- 0.9	- 0.7	10.9	0.09
B	+ 0.1	- 1.0	7.5	0.02
C	- 1.2	- 2.6	6.2	0.29
D	- 0.3	- 1.0	6.5	0.05
E	- 1.1	- 1.1	9.2	0.12

4. Conclusion

This paper presents an experimental study on energy savings due to conservation voltage reduction under laboratory conditions. Five CVR units, which are commercially available on the market, were experimentally investigated. The influence on the total power consumption, the useful work of five different load groups as well as the influence on THD of the current and voltage were investigated.

It can be concluded that, the reductions in power consumption of the five CVR units differ significantly. For a voltage reduction of 10 %, savings between 0.6 % and 5.9 % can be calculated. When examining different load groups, no significant savings can be measured for SMPS, motors with FC or LED lighting. Savings of 15.8 % on average can be measured for halogen spotlights. For fluorescent tubes, savings of 6.3 % on average can be achieved. For halogen spotlights and fluorescent tubes, it must be taken into account that the illuminance decreases significantly. With the exception of unit C, no significant influences on of the current THD_I or the voltage THD_U can be measured. In general, it can be stated that the THD_I increases while the THD_U decreases slightly.

Replacement of old halogen spot lights and fluorescent tubes by more efficient LED technology can be a more cost-effective measure to reduce energy consumption than the use of CVR systems. It shall be mentioned that CVR units can help to protect loads from high voltage, which can increase the lifetime of equipment and avoid additional costs. These effects, as well as the influence of cable lengths or unstable power grids (see [14]), have not been investigated in this work and can therefore not be quantified.

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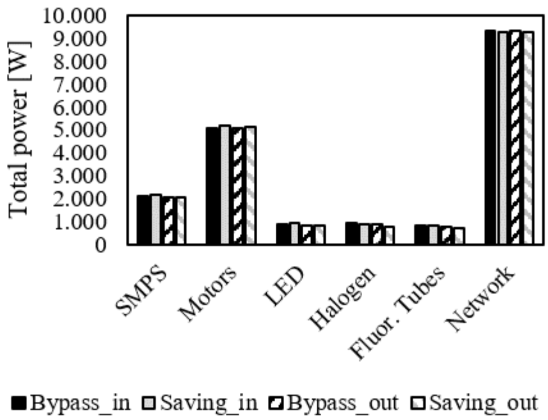
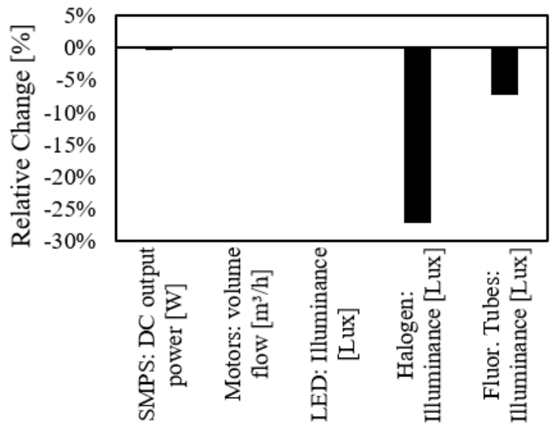
A. 1: Measurement Data

Total active power consumption in Watt for all load groups (LG) and network measurements (left) and the relative change in output of each load in network measurement (right)

Unit A:





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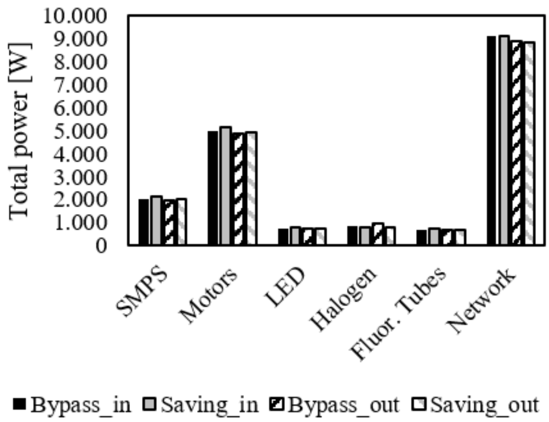

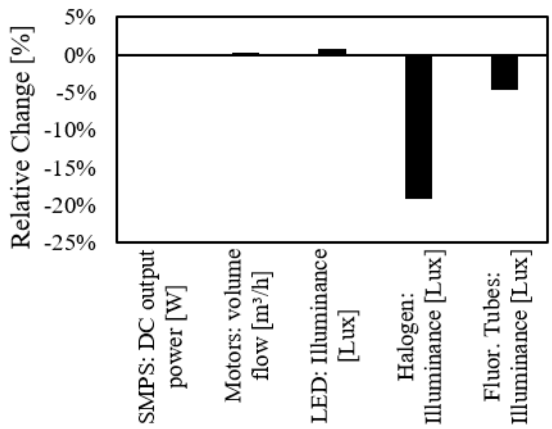

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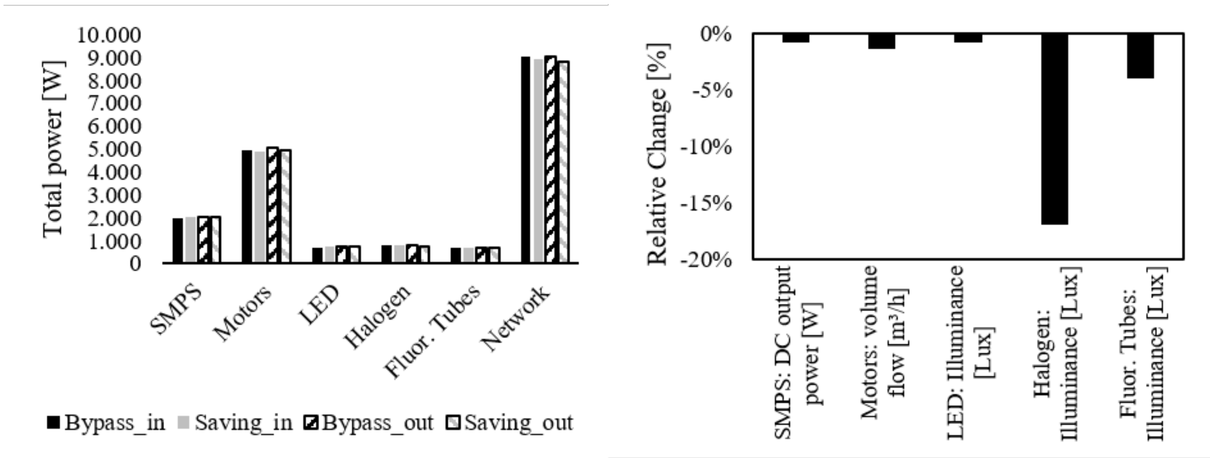
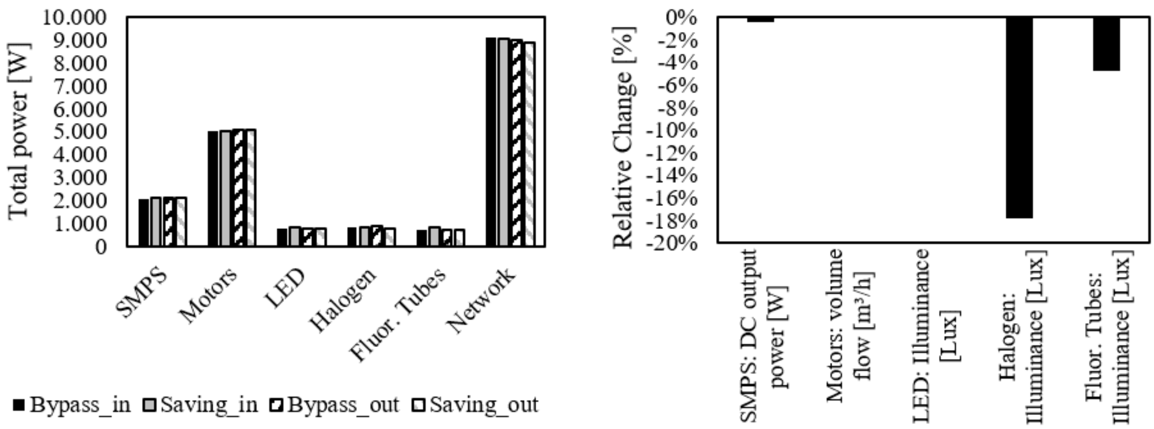


Unit D:



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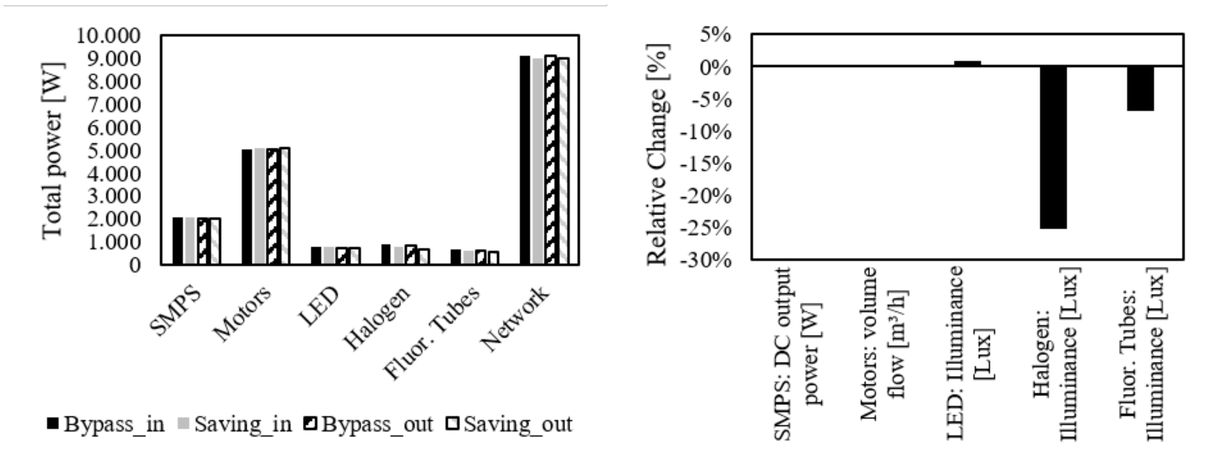

B. 2: Abbreviations

AC	alternating current
ACM	absorption chilling machine
CVR	conservation voltage reduction
DC	direct current
FC	frequency converter
LG	load group
PLC	programmable logic controller
SMPS	switching power supply
THD	total harmonic distortion