

Utilization of the standard-voltage-range in low-voltage networks for the usage of Local-Energy-Controllers without affecting the power-quality

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Abstract—Low-voltage-networks operate with a nominal voltage charged with a tolerance range. Consumer's installations (CI) are fed with different supply-voltages which depend on the location of the CI within the LV-grid and the load flow. At the feeding point of the CI no additional regulating device is foreseen. Local-Energy-Controllers can decrease the supply-voltage and influence the energy consumption of the CI. This paper shows when LECs operate properly and which preconditions have to be fulfilled for the energy-saving. Different consumer categories and the calculation algorithm for the amount of the energy saving will be introduced. At the end the algorithm will be compared with results of real LEC-installations. The properly engineered operation of an LEC saves energy, energy costs and reduce CO₂, without affecting the power-quality negatively.

I. INTRODUCTION

Electric low-voltage-networks are designed for a rated voltage U_n . Due to topological and load flow reasons the nominal voltage is charged with a tolerance, so that the supply-voltage at the feeding-point of the consumer's installation is

$$U_S = U_n + \Delta U/U_n; \quad (1)$$

U_S supply-voltage,
 U_n nominal voltage of the low voltage network,
 $\Delta U/U_n$ voltage tolerance in % (e.g. $\pm 10\%$)¹.

Typical connection of the CI is indicated in Fig 1.

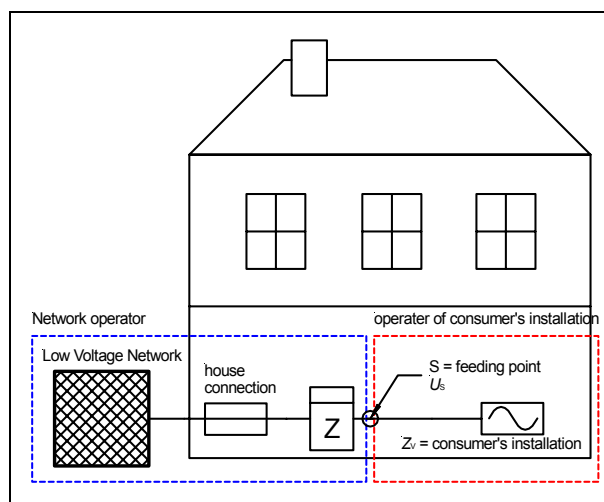


Figure 1. Typical infeed to consumer's installation on low voltage level

In accordance with the requirements of EN 50 160 and IEC 60038 the supply-voltage can reach the lower or superior limit.

Presently there is no regulation of the supply-voltage foreseen at the feeding point. The result of the missing regulation possibility is

- varying energy consumption of the CI and
- interfering voltages at the superior limit.

To be in the position to counteract these effects Local-Energy-Controllers (LEC) help. With the reduced voltage level (but still in accordance with valid regulations) energy can be saved without affecting the power-quality. In the following the calculation algorithm and the LEC operation will be introduced.

¹ Refer to IEC 60038

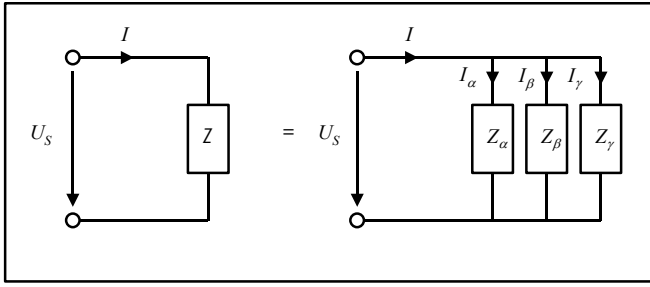


Figure 2. circuit diagram of consumer's installation and equivalent circuit diagram

Furthermore results of already installed LEC's demonstrate the calculation algorithm.

II. CONSUMER'S INSTALLATION (CI)

A. Energy consumption of the CI

Each CI can be substituted by an equivalent circuit diagram as shown in **Fig 2**.

The energy² supplied to the CI is defined as

$$W = P \cdot t; \quad (2)$$

W electric energy,
 P active power,
 t hours of operation.

P depends on the voltage U_S and the current I (refer to **Fig. 2**):

$$P = U_S \cdot I \quad (3)$$

with $I = U_S/Z$ the energy consumption can be indicated as

$$W = (U_S^2/Z) \cdot t. \quad (4)$$

If the characteristic of all electric resistances were linear the energy would only depend on the supply-voltage U_S and the hours of operation t with $Z^2 = \text{const.}$ for each supply-voltage. As this is not realistic we have to release such categories for the different electric equipment so that we are in the position to define on which kind of consumers (4) can be applied for different voltage levels.

B. Categories of electrical equipment

There are three different kinds of electric equipment in each CI. It can be divided in:

- on voltage depending equipment (α -equipment), such consumers are referenced with α , the resistance is Z_α and the current is I_α ,
- power-constant equipment (β -equipment); such equipment is referenced with β , the resistance is Z_β and the current is I_β , and
- energy-constant equipment (γ -equipment); such equipment is referenced with γ , the resistance is Z_γ and the current is I_γ .

The U - I -characteristic and the energy consumption of α -equipment is indicated in **Fig. 3** which shows that the power (area $U \cdot I$, left figure) will be reduced quadratic when reducing the supply-voltage U_S . The energy consumption of α -equipment is

$$W_\alpha = (U_S^2/Z_\alpha) \cdot t. \quad (5)$$

The degree of voltage reduction is referenced with u ($u = 0 \dots 1$). The energy consumption of α -equipment after reducing the voltage at about u is

$$W'_\alpha = ([U_S^2 \cdot (1-u)]^2/Z_\alpha) \cdot t. \quad (6)$$

The U - I -characteristic and the energy consumption of β -equipment is indicated in **Fig 4**, the energy consumption of β -equipment is

$$W_\beta = (U_S^2/Z_\beta) \cdot t. \quad (7)$$

After reduction of the supply-voltage at about u the reduced voltage is

$$U_S' = U_S \cdot (1-u) \quad (8)$$

and the current is

$$I_\beta' = I_\beta / (1-u). \quad (9)$$

The energy-consumption after reducing the voltage is

$$W_\beta' = U_S \cdot (1-u) \cdot I_\beta / (1-u) \cdot t = W_\beta. \quad (10)$$

The result of (10) shows that there is no energy-saving on β -equipment by the use of reduced supply-voltage.

The U - I -characteristic and energy-consumption of γ -equipment is indicated in **Fig 5**.

² Only the active Power P is to be considered.

³ For the energy-calculation only the real part of Z is considered.

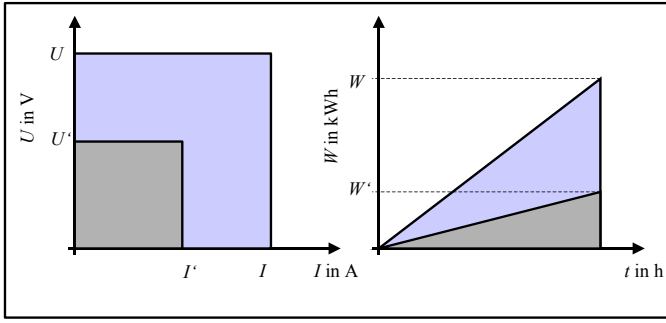


Figure 3. U - I -characteristic and energy consumption of α -consumers

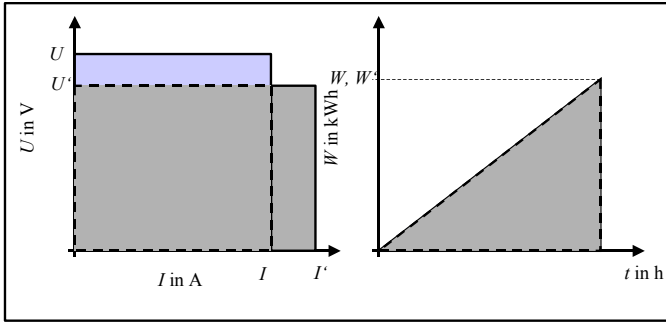


Figure 4. U - I -characteristic and energy consumption of β -equipment

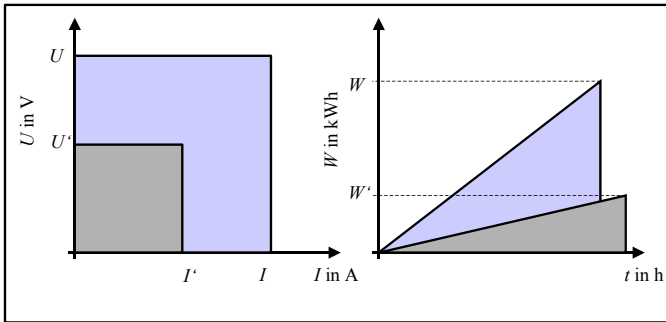


Figure 5. U - I -characteristic and energy consumption of γ -equipment

The power-characteristic of γ -equipment is similar to the characteristic of α -equipment but the characteristic of operation time is different. The hours of operation will be extended up to

$$t' = t/(1-u)^2. \quad (11)$$

For the calculation of the energy-consumption after reducing the supply-voltage by u we can take (6) and (11) which leads to

$$W_{\gamma}' = ([U_S \cdot (1-u)]^2 / Z_{\gamma}) \cdot t/(1-u)^2 = W_{\gamma}. \quad (12)$$

No energy can be saved on γ -equipment by reducing the supply-voltage.

C. Calculation of energy-savings of the CI supplied with reduced voltage

In clause B. we learned that energy-savings can only be affected on α -equipment. Each CI is a mixture of α , β and γ -equipment so that the circuit diagram can be transferred as indicated in Fig. 2. To calculate the energy-saving by supplying the CI with reduced voltage the degree of α -equipment has to be known.

We take a reference period (e.g. one year) in which the CI consumed energy. The energy-saving compared to the energy-consumption of the CI during the reference period can be calculated as follows.

According to Fig 2 the energy-consumption during the reference period is:

$$W = W_{\alpha} + W_{\beta} + W_{\gamma}. \quad (13)$$

To calculate the energy-consumption of the CI with reduced supply-voltage we take (6), (10) and (12):

$$W' = W_{\alpha}' + W_{\beta} + W_{\gamma}. \quad (14)$$

The energy-saving in comparison to the reference period is

$$\Delta W = W - W' = W_{\alpha} - W_{\alpha}'. \quad (15)$$

For the currents I_{α} , I_{β} and I_{γ} we can write

$$I_{\alpha} = \alpha I \text{ with } \alpha = 0 \dots 1, \quad (16a)$$

$$I_{\beta} = \beta I \text{ with } \beta = 0 \dots 1, \quad (16b)$$

$$I_{\gamma} = \gamma I \text{ with } \gamma = 0 \dots 1 \text{ and } \quad (16c)$$

$$\alpha + \beta + \gamma = 1. \quad (17)$$

Equation (6) then can be written as

$$W_{\alpha}' = U_S \cdot (1-u)^2 \cdot \alpha I \cdot t \quad (18)$$

With (15) and (18) we get

$$\Delta W = U_S \cdot I \cdot \alpha \cdot t - U_S \cdot (1-u)^2 \cdot \alpha I \cdot t,$$

$$\Delta W = U_S \cdot I \cdot t \cdot u \cdot \alpha \cdot (2-u). \quad (19)$$

The energy-saving is referenced to the energy consumption of the reference period. The result is

$$\Delta W/W = u \cdot \alpha \cdot (2-u). \quad (20)$$

Equation (20) is the common formula how to calculate the energy saving of each CI by reducing the supply-voltage.

Example 1

The energy-consumption of a drugstore is

$$W = 300\,000 \text{ kWh/a.}$$

The degree of α -equipment is 90 % (i.e. $\alpha = 0,9$). The supply-voltage shall be reduced by 8 % (i.e. $u = 0,08$). The calculated energy-saving then is

$$\Delta W/W = 0,08 \cdot 0,9 \cdot (2-0,08) = 0,138 = 13,8 \text{ \%}.$$

The absolute amount of energy-saving is

$$\Delta W = 300\,000 \text{ kWh/a} \cdot 0,138 = 41\,400 \text{ kWh/a.}$$

III. REDUCTION OF THE SUPPLY-VOLTAGE BY USING LOCAL-ENERGY-CONTROLLERS (LEC)

Chapter II indicated how to calculate possible energy-savings, in this chapter we will indicate in which way the supply-voltage can be reduced and which critical items have to be considered. LEC can be located at the feeding point of the CI (refer to **Fig. 6**). To locate a LEC at the central feeding point it has to be assured that the power quality for the CI will not be affected negatively. Therefore the new supply-voltage U_S' has to fulfill the same requirements as the supply-voltage U_S , i.e.

$$U_n - 0,1 \cdot U_n < U_S' < U_n + 0,1 \cdot U_n \quad (21)$$

Furthermore the capability of the CI shall not be decreased and the losses of the LEC must be kept at a minimum. The LEC shall not generate additional harmonics.

The practical realization of the requirements are:

- monitoring the supply-voltage U_S and/or U_S' ,
- monitoring the load flow via the LEC.

In case of reaching one of these limits the LEC has to be by-passed or regulated in such a way that the supply-voltage U_S' fulfill the requirements of IEC 60038.

A. LEC in service

In real installations LECs manufactured according to DIN EN 60730-2-11 are equipped with the following features:

- switchable transformer,
- monitoring of the supply-voltage level,
- monitoring of the current, due to overload reasons,
- automatic by-pass-switch.

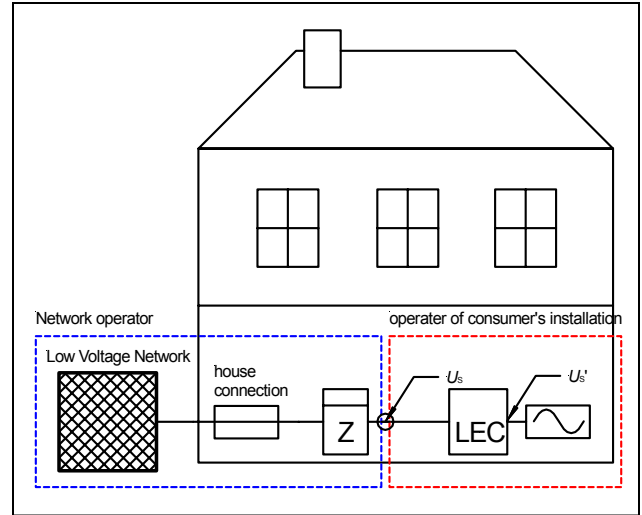


Figure 6. Location of Local Energy Controller in the CI

The voltage reduction is to be carried out by an transformer as stated in **Fig 7**.

This LEC has been installed in a lot of CI's. The results of the energy-saving have been tested on this type of LEC. Mostly the range of $S = 150 \text{ kVA}$ has not been exceeded. The by-pass-switch has to be operated either if the voltage level on output side is to low or if the load through the transformer is higher then it is designed for. The degree of energy-saving can be measured by two conditions

- transformer in service (i.e. by-pass-switch open),
- transformer out of service (i.e. by-pass-switch closed).

The result of the measurement is shown in **Fig. 8**.

Voltage and current are measured at point s (Fig. 2), i.e. on the input side of the LEC. Before the installation the α -degree was calculated as

$$\alpha = 0,9,$$

the voltage reduction is adjusted to

$$u = 0,08,$$

i.e. $\Delta U/U_S \cdot 100 \% = 8 \text{ \%}$. The energy-saving was calculated according to (20), i.e.

$$\Delta W/W = 0,9 \cdot 0,08 \cdot (2-0,08) = 0,1382 = 13,8 \text{ \%}.$$

The result of the measurements at the LEC in service is (refer to the figures in **Fig. 8**):

$$U_S \approx \text{constant},$$

$$\Delta I/I = 13,1 \text{ A} / 98,7 \text{ A} = 0,1327 = 13,27 \text{ \%}.$$

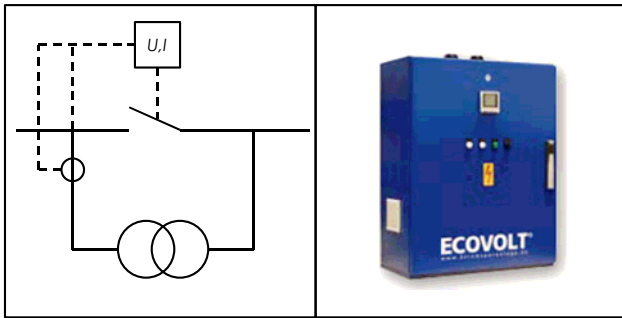


Figure 7. LEC in accordance with DIN EN 600730-2-11⁴

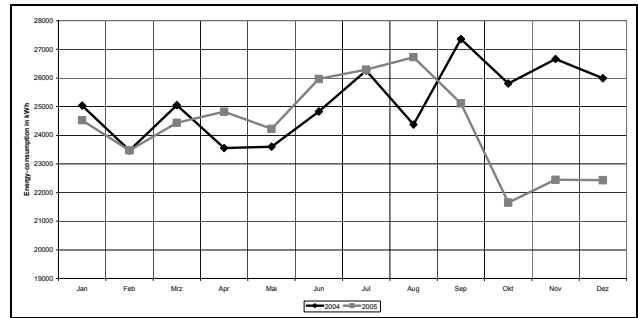


Figure 10. Energy consumption of reference period and period with installed LEC (installation date 30.09.2005)

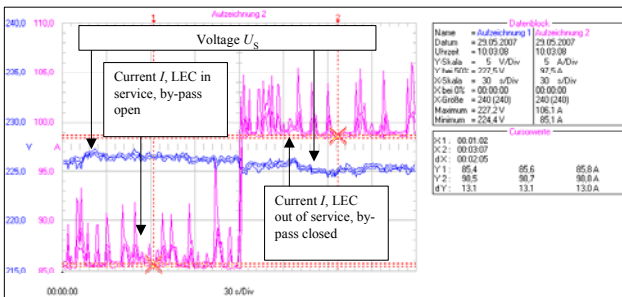


Figure 8. U - I -characteristic of a CI with activated and deactivated LEC

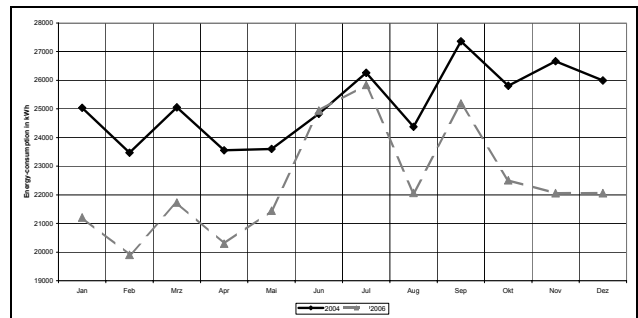


Figure 11. Energy consumption of reference period and actual (2006) energy-consumption

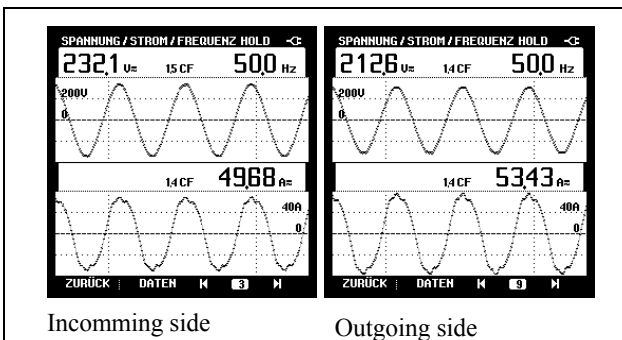


Figure 9. U - I -characteristic at incoming and outgoing side of LEC

As the losses of the LEC are $w_1 < 1\%$ the calculated result is nearly the same as the result of the real measurements. The voltage level of incoming and outgoing side of LEC is shown in Fig. 9.

Furthermore the power quality was measured according to EN 50 160. Two measurements were carried out

- in front of the LEC and
- behind the LEC.

Both results stated that the power quality is in required range and in accordance with EN 50 160.

B. Longterm experience with LEC in service

In the longterm view the energy consumption of a CI has been compared with the consumption of the reference period. The result of this comparison is stated in Fig. 10. The black curve indicates the energy consumption of the reference period, i.e. 2004. the grey curve indicates the energy consumption of the following year. The LEC was installed on 30.09.2005. Up to September 2005 the grey curve is nearly similar to the black one. From October 2005 the energy consumption drops down to a level of 84 ... 87 % of the reference period.

Fig. 11 indicates the results of 2006 compared with 2004. The energy-consumption in 2006 is in average 11 % less than in 2004. In the months June and July the consumption in 2006 is as high as the consumption in 2004. The reason is that the energy demand in these months was higher than in 2004 (due to additional cooling). There is no negative influence in the CI with the LEC operating. The total energy-saving in 2006 was 32 785 kWh/a. Actually the higher demand in June and July 2006 has to be considered, so that the actual saving is 39 262 kWh/a.

Without having any negative effects in the CI the LEC saves energy in the range of 10 ... 16 %.

⁴ Source: Picture by courtesy of Jäger Direkt GmbH & Co. KG, DE-64385 Reichelsheim, Hochstraße 6, www.ECOVOLT.de

C. Precondition for LEC-Installations

LECs can only be installed at those locations where the following preconditions are fulfilled:

- the supply-voltage U_S at the feeding point must be at adequate level (i.e. $U_S > 0,95 \cdot U_n$),
- the LEC must not generate additional harmonics,
- the power quality behind the LEC must not be worse than in front of it,
- the α -degree must be in an adequate range (at least 40 %),
- the LEC shall be equipped with a by-pass-switch, so that CI can also be supplied with U_S ,
- monitoring of voltage and current should be available.

If the LEC and the conditions of the CI meet the a.m. requirements LECs will save a lot of energy. Beside the energy saving this is furthermore a reduction of energy costs and reduction of CO_2 . This is for the a.m. example a CO_2 -reduction of 26 815⁵ kg CO_2/a .

IV. GENERAL USE OF LEC

As mentioned in the introduction different supply-voltages are necessary due to topological and load flow reasons. Normally it depends on the distance to the next MV-transformer-station. If we consider these preconditions the range down to $0,95 \cdot U_n$ can be utilized for operating an LEC (refer to **Fig. 12**). Due to the reason that the CI shall work properly without having any negative effects with the operation of an LEC, the installation has to be engineered properly.

V. OUTLOOK

According to directive 2006/32/EC the energy end-use efficiency is to be increased in European countries. The energy efficiency is defined as

'ratio between an output of performance, service, goods or energy and input of energy'

In consideration of this definition LECs are very interesting for all energy service companies (ESCOs) and distribution system operators to spend additional advantages to there customers as well as for all end-users and operators of CIs.

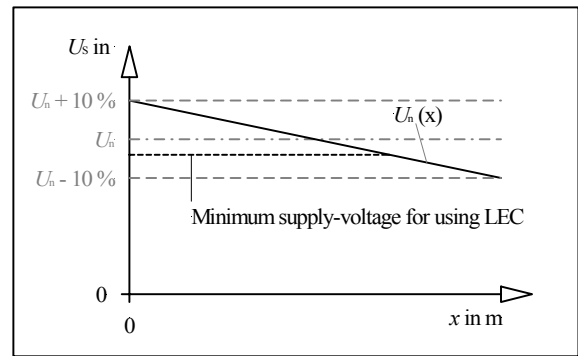


Figure 12. Range in which LECs can operate

SUMMARY

LECs help to save energy. The application has to be designed properly to avoid any negative effects. The degree of energy-savings in comparison to the consumption of a reference period can be calculated according to (20), i.e.

$$\Delta W/W = u \cdot \alpha \cdot (2-u).$$

The results of already designed and installed applications with LECs indicate that energy-savings without affecting the power quality can be achieved. For the correct design of LECs precondition have to be fulfilled.

The utilization of the standard voltage range in the low-voltage-grid for running an LEC can be estimated at about 70 %. Beside the energy-saving CO_2 can be reduced.

Especially to reach the aim of the energy efficiency raise as stated in directive 2006/32/EC LECs could be an important part of this strategy.

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⁵ this value is calculated under German conditions. In Germany the emission of CO_2 concerning electricity is $m_{CO_2} = 0,683$ kg / kWh