Lappeenranta University of Technology
LUT School of Energy Systems
Degree Programme in Electrical Engineering
DIODE-Programme

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REACTIVE POWER COMPENSATION WITH A UPS UNIT

Examiners:	Professor Jarmo Partanen
	Post Doc Jukka Lassila
	M.Sc. Juha Kuuluvainen

ABSTRACT

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There is a demand for the compensation of reactive power due to its surplus contents and tariff charges in Finland. The goal of this thesis work was to form a conclusion to the viability of such compensation to be performed with the uninterruptible power supply (UPS). Two theoretical approaches were covered by its centralized compensation: offering reactive power capacity to the local distribution system operator as a grid service and by a compensation of the local site's reactive loads.

The study method was conducted by referring to standards, measuring the UPS efficiencies during different operation points, and by calculating the annual savings and operation costs in the example scenarios. Sensitivity analyses were carried out with different annual hours of utilization and UPS rated load levels.

The UPS efficiency decreases respectively to the increased reserve power capacity and lower load level. However, the end results show that the example scenarios are profitable in all the studied cases. Three out of the four most profitable cases show that the achieved savings are always proportional to the increasement of the reserve power demand. The results do not include investment costs.

THE FIRST WORDS

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Juho Räsänen, Espoo 22.6.2020

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LIST OF ABBREVIATIONS AND SYMBOLS

BESS	battery energy storage system
BMS	building management system
DC	data center
DSO	distribution system operator
EESS	electrical energy storage system
FCR	frequency containment reserve
IGBT	insulated gate bipolar transistor
LV	low voltage
MV	medium voltage
NPC	neutral point clamped
PF	power factor
PFC	power factor correction
PQ	active reactive power
PWM	pulse-width modulation
RP	reactive power
RPC	reactive power compensation
STS	static switch
TSO	transmission system operator
UPM	universal power module
UPS	uninterruptible power supply
V	mains source voltage
$\mathrm{V}_{\mathrm{mod}}$	fundamental voltage
U_n	nominal voltage
$RP_{genmode}$	RP generation mode enabled
P_D	design active power
S_{max}	maximum input apparent power
P_{input}	drawn UPS input active power
$Q_{setpoint}$	reactive power setpoint
φ_1	displacement angle between voltage and current
P_{rest}	parallel load

S_{input}	drawn UPS input apparent power
Q_{max}	UPS maximum input reactive power
U_s	rated UPS input voltage (L-L)
I_{max}	maximum phase RMS supply current
r_{ph}	phase resistance for the supply cable
x_{ph}	phase reactance for the supply cable
S_n	transformer nominal apparent power
R_t	transformer’s resistance at the secondary side
X_t	transformer’s reactance at the secondary side
l	length of the supply cable
u_k	transformer’s relative short-circuit voltage

1 INTRODUCTION

The UPS owners can possess reserve power capacity due to high level of redundancy and fault tolerances involved for protection of their end loads. The total UPS system nominal power can be megawatts, and the corresponding load level 25 % for Tier 4 data centers e.g. This creates possibility for auxiliary services for the UPS while providing conditioned power to its end loads. Currently, it has been noticed that the systems including both power electronics and energy storages have a potential to participate to active power related markets and utilize reactive power compensation against tariff prizing [1]. In Finland, a new tariff concerning reactive power surpluses of the DSOs (distribution system operators) was introduced in 2017 [2]. Accordingly, DSOs have regional tariffs concerning their own end customers. There is also a research ongoing for the creation of reactive power related market place [3].

In this thesis work the viability of a dynamic reactive power compensation (RPC) will be studied by two example business cases for local compensation. In the beginning of thesis, principle of the UPS and its bidirectional rectifier will be presented. Then the standards will be reflected based on the current requirements addressing the reactive power capability in the electrical energy storage systems (EESS). Measurements will be taken to analyze how the UPS efficiency will be affected during its double conversion mode with an additional inductive and capacitive operation features. These will be linked to the chosen UPS input PQ window (active reactive power). Excessive injection of the reactive power is seen as a grid supportive action to diminish its surpluses of the reactive power content.

In the end, the results will be analyzed by theoretical calculations. Those are reflected to the tariff pricing concerning both the DSO and the end customer. Annual savings and cost of operation are formed when the grid service occurs and are compared to the default state. Sensitivity analyses are carried out with the total injection hours and different rated load levels which address the available compensation capacity. Per unit revenues (€/kvar) are then formed for the most profitable scenarios. The thesis scope focuses on the double conversion UPS and injecting reactive power with fundamental frequency.

2 PRINCIPLE OF A UPS

2.1 Operation and main components

The purpose of UPS (uninterruptible power supply) is to provide uninterrupted and conditioned power to its critical end loads, against the supply grid's power failures, voltage fluctuations, power spikes or other disturbances. In the double conversion UPS, power conversions are done from the input AC to DC with the rectifier and from DC to AC with the inverter. [4]. During its double conversion mode which is referred to normal operation mode here, rectifier draws power from the grid and produces regulated DC-voltage for the inverter. The inverter produces a regulated and filtered three-phase AC output to the end loads. Current path during the normal mode is shown in Fig. 1 [5].

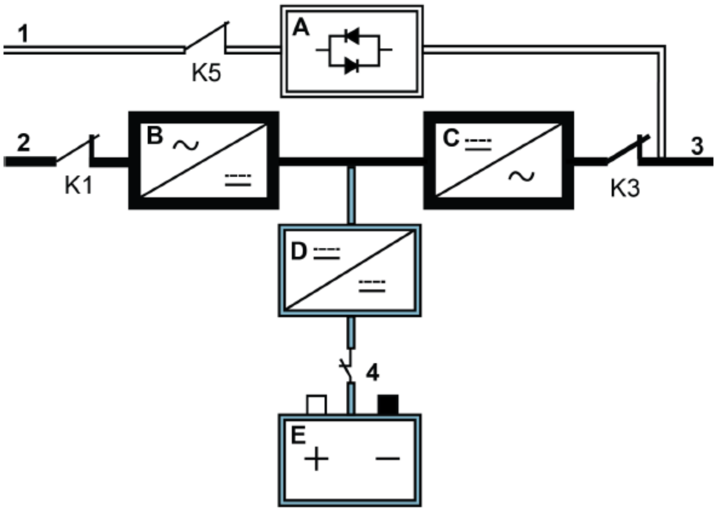

Figure 1. The current path highlighted during the double conversion mode. [5].

If the utility power outage occurs, the power is automatically drawn from the batteries to the inverter. The current path during the battery mode of operation is shown in Fig. 2.

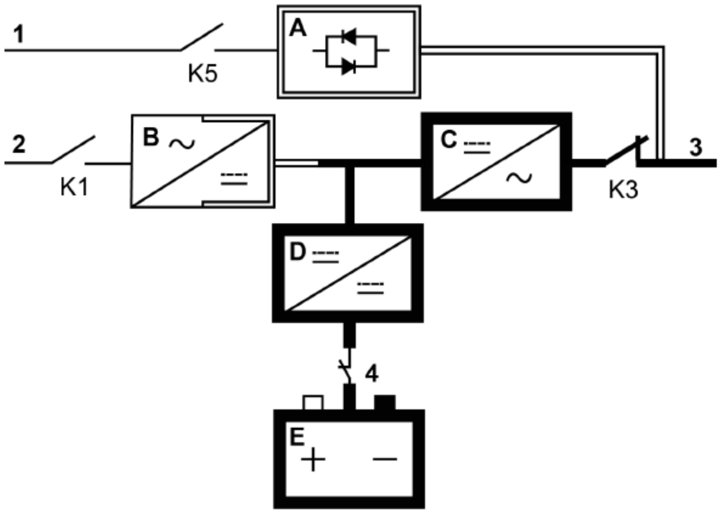

Figure 2. The current path highlighted during the battery mode of operation. [5].

UPS main components are consisting of independent universal power modules (UPMs), battery converter, internal or external batteries and thyristor-based static switch (STS). A single UPS-cabinet can consist of multiple parallel connected UPMs. Also, UPS cabinets can be connected externally parallel. [4]. Eaton 93PM 50 kW UPS internal main components in a single line diagram is shown in Fig. 3.

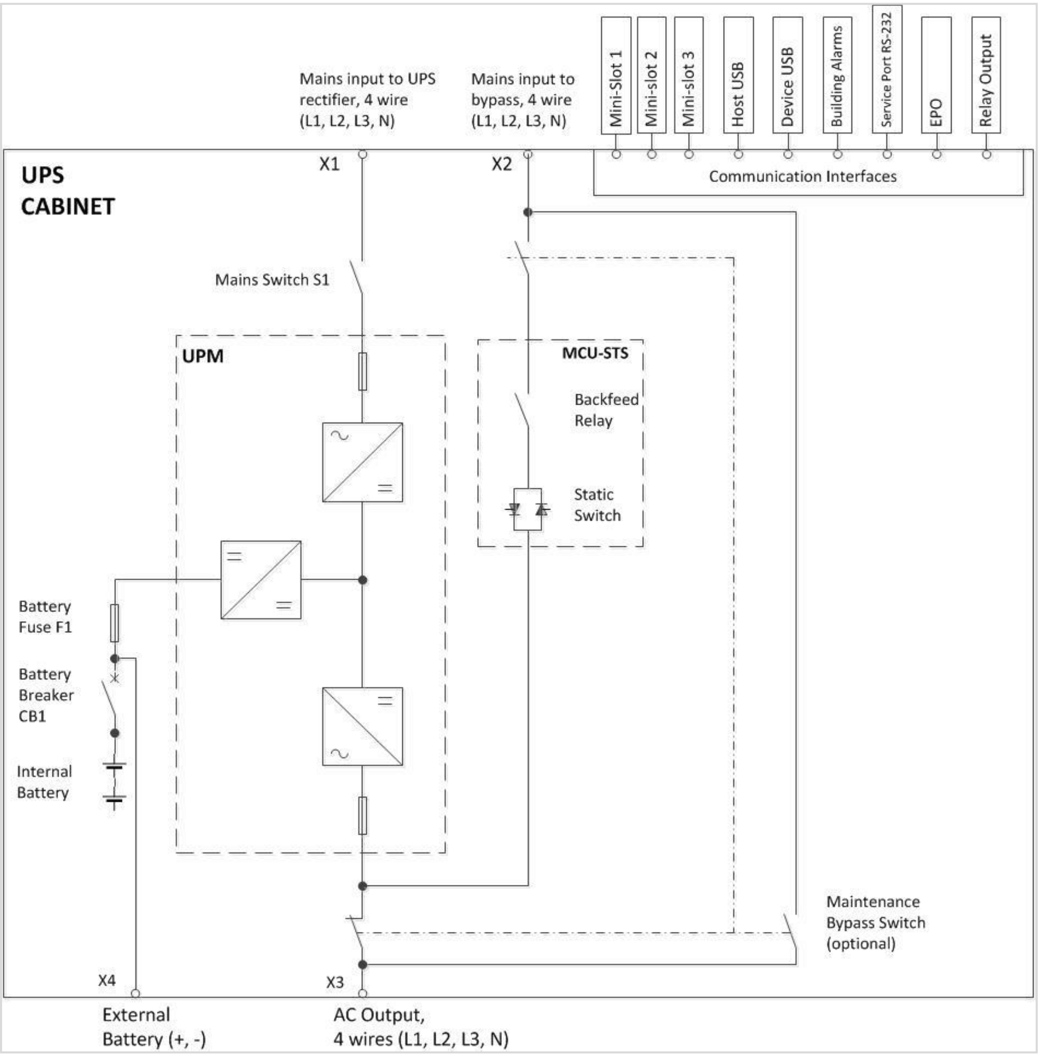

Figure 3. UPS internal main components in a single line diagram.

2.2 Three-level rectifier

In this thesis, the UPS consists of 3-phase 3-level NPC (neutral point clamped) voltage source bidirectional rectifier and inverter. In the below Fig. 4, 3-level NPC-topology is shown for a single-phase leg of the rectifier supplied from the input source.

When compared to conventional 2-level topology, the 3-level NPC-topology allows the phase input or output connection to the neutral point in addition to the DC-link voltages DC+ and DC-. Resulting advantage is the improved output voltage quality. Commutation voltage is reduced to half, and the switching losses can be roughly also estimated to be reduced to half in 3-level topology [6]. Neutral connection is utilized by the two NPC-diodes for each phase leg for positive and negative current paths. [7]. At the rectifier’s side, these diodes are marked as D5-D6 accordingly to the below Fig. 4.

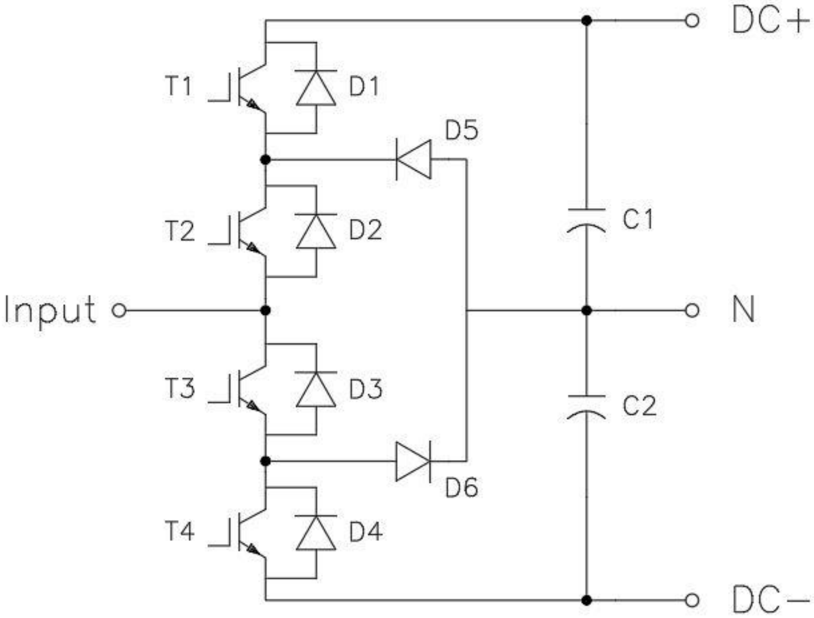

Figure 4. 3-level NPC-topology rectifier drawn for a single-phase leg.

During the positive half-cycle of the input voltage source, IGBT (insulated gate bipolar transistor) semiconductor device pairs T1-T2 and T2-T3 are controlled to connect the input phase to DC+ and neutral N [8]. While the source current is positive, T1-T2 are triggered for DC+ connection and diodes D1-D2 are commutated for the positive current path. From this state the neutral-point can be connected by opening T1 and triggering T3 on. Its current path is formed by commutating devices T3 and D6. From this state DC+ connection is again formed by first opening the T3 and then triggering T1 on.

During the negative source voltage, the procedure is the same for connecting -DC and N with the device pairs T3-T4 and T2-T3 accordingly. The device switching can be irrespective of the source current direction [8]. This is showcased in the next chapter for the RP (reactive power) injection.

2.3 Four-quadrant operation

The principle idea of utilization of the active rectifiers is to draw input current which stays in line with the supply voltage. Both harmonic current reduction and the phase displacement correction can be utilized with PWM (pulse-width modulation scheme) to modify the drawn input current. The UPS rectifier was programmed to operate below the unity power factor by adjusting the amplitude of the PWM generated voltage with respect to the reference source voltage of the mains.

For simplicity, the example capture in Fig. 5 shows the principle of operation in four quadrants as a phasor diagram of the 2-level force-commutated rectifier. The amplitude and phase of the PWM generated fundamental voltage (V_{mod}) is adjusted with respect to the mains source voltage (V). [9].

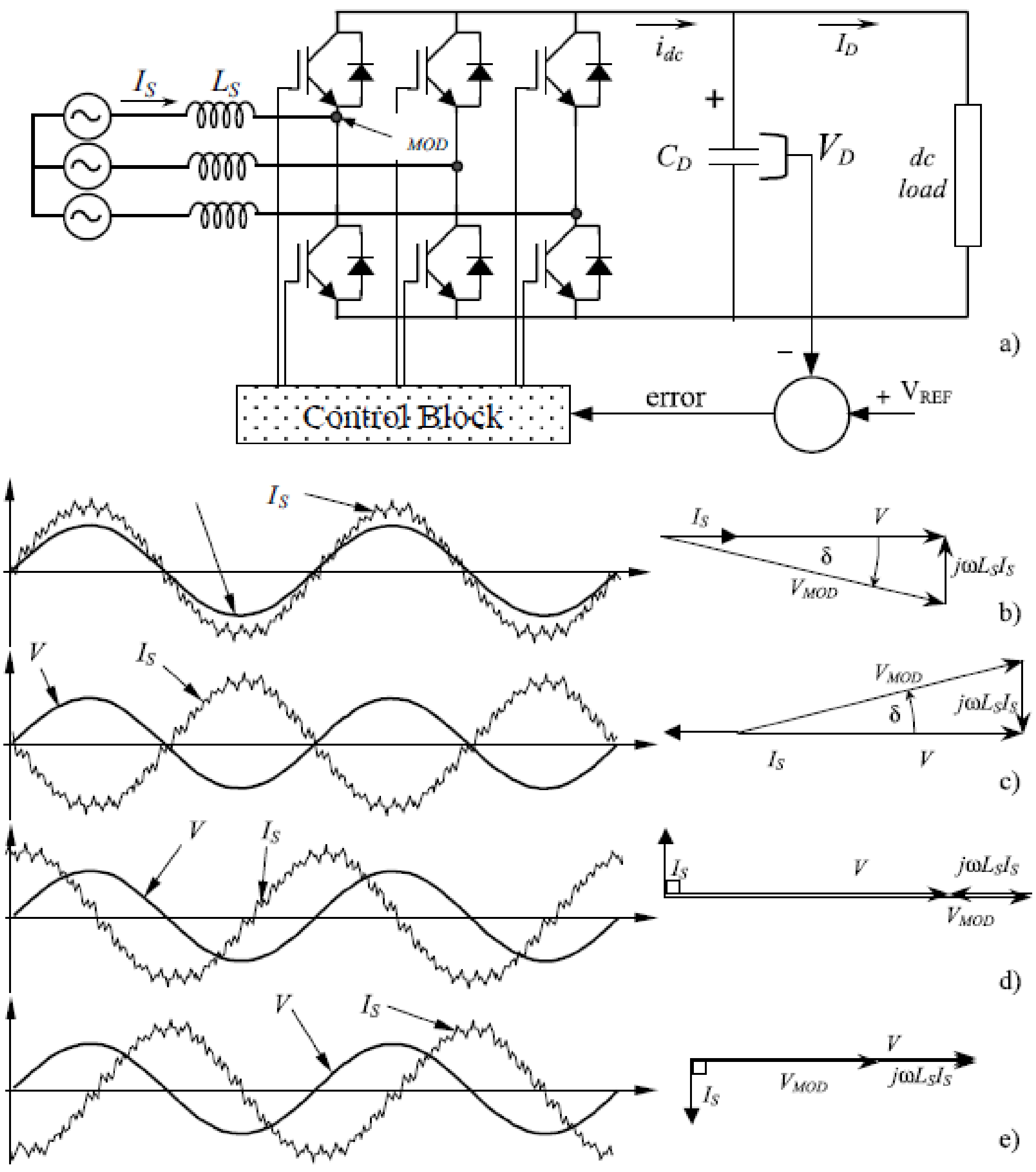

Figure 5. The example of "four-quadrant operation of the force-commutated rectifier: a) the PWM force-commutated rectifier; b) rectifier operation at unity power factor; c) inverter operation at unity power factor; d) capacitor operation at zero power factor; and e) inductor operation at zero power factor." Figure is a capture from the reference source [9].

3 REACTIVE POWER COMPENSATION

3.1 Background

In this thesis the reactive power compensation or power factor correction (PFC) refers to increasing the power factor between the active and apparent power components. The power factor is the cosine of the same angle that can be noted as a displacement angle (shift) between the voltage and current components. Accordingly, the PFC can also mean minimizing the angle between the voltage and the current. This relationship is drawn to Fig. 6 below [10]:

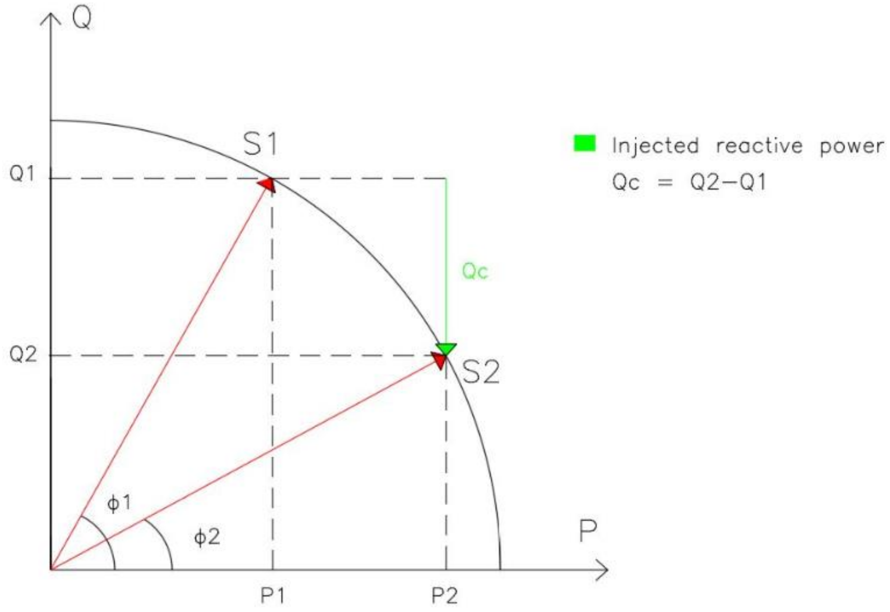

Figure 6. Vector diagram showing the relationship between the power factor and its correction by external injection of reactive power. The phase angle φ_1 is reduced to φ_2. Figure is redrawn from the reference source [10].

In AC network, the reactive power (RP) is power that is generated to magnetic fields causing additional losses. Depending of the type of loads and their variations, the need for reactive power compensation is associated to [10, 11]:

- Reactive power drawn for loads utilizing magnetic fields (motors and their starting, transformers, overhead power lines)
- Reactive power consumed by capacitive loads (lightning, underground cables e.g.)

- Other generated losses, voltage regulation, tariff or charges
- Harmonics generated by various power electronics

Inductive loads generating reactive power causes phase shift between voltage and current which is noted as lagging power factor, as the current lags the voltage. In the capacitive loads case, the power factor is leading as the current leads the voltage. In purely inductive or capacitive cases the phase difference is 90 degrees accordingly. [11].

In the following chapters UPS is evaluated to have a feature of the central compensation device. Central compensation has traditional meaning to capacitor banks that can be controlled automatically based on the varying RP requirements in LV and MV networks. [10]. In here, the UPS has dynamic compensation capability for its inductive and capacitive operations.

The UPS is a part of the generating plants (sites) that are connected to LV (low-voltage $U_n \leq 1$ kV) and MV (medium voltage 1 kV $< U_n \leq$ 1 kV) distribution networks. UPS is evaluated to be type A or B -rated generating module. Generating module means here that the UPS-system can consist of the set of generating units. These generating units can be parallel connected UPMs within the UPS. Generating plant is a sum of generating modules at one point of connection (POC). In Finland, TSO Fingrid states that the type A generating plant's max. active power is (0.8 kW $\leq P_{max} <$ 1 MW), type B (1 MW $\leq P_{max} <$ 10 MW), and type C (10 MW $\leq P_{max} <$ 30 MW) [12].

3.2 Generating plant LV-connection

European Standard EN 50549-1:2019 covers requirements for generating plants up to type B and included, which are to be connected in parallel to a LV distribution networks. In general, the generating plants needs to provide support against the voltage changes out of acceptable limits, if it is required by the DSO and the responsible party. The limits are defined by national regulation. The following mentioned notes are considered here, when the UPS is providing voltage support by reactive power as a generating unit with non-synchronous generating technology [13]:

- Requirements for operational capabilities during the throughout continuous operating frequency and voltage with design active power P_D (= 0.9 underexcited or overexcited) capability shown in Fig. 7. Design active power: "maximum AC active power output at an active factor of 0.9 or the active factor specified by the DSO or the responsible party for a certain generating plant or generating technology – under sinusoidal conditions, the power factor is the absolute value of the active factor."
- The RP capability is evaluated at the terminals of the unit
- The DSO and the responsible party may relax the requirements above

It is also mentioned, that each unit within generating plant shall provide voltage support by reactive power as required for its specific technology, and that the compensation of one technology to reach the general plant requirement is not expected. This is also part of the above requirements to be possibly relaxed when agreed, and in this thesis the capability of the UPS technology increasing the generating plant's power factor is evaluated. The UPS technology would then aid to meet the general plant requirement at the DSO connection point, which is the POC. The standard notes that for additional network support, an optional extended reactive power capability can be provided by the generating plant. It needs to be agreed between the DSO and the producer and is generally required in some countries for some technologies by legal regulations. Extended reactive power forms an area outside the requirement-triangle in Fig. 7. In this thesis, the RPC as a grid service would require the agreement of the local DSO for diminishing its surpluses of the RP content. Accordingly, it requires even more extended PQ window from the RP perspective. The generating plant throughout continuous operating voltage and frequency ranges at the POC are within 85 % to 110 % of the nominal voltage U_n, and 49-51 Hz of the frequency respectively. Beyond the mentioned voltage values, the under and over voltage ride through -immunity limits specified by the standards apply but are not covered within this thesis. Within the frequency range of 47-52 Hz, the generating plant should be capable of operating until tripping of any interface protection. The generating units with non-synchronous generating technology should stay connected with the distribution network with 2 Hz/s rate of change of frequency, if no other value is specified by the responsible party.

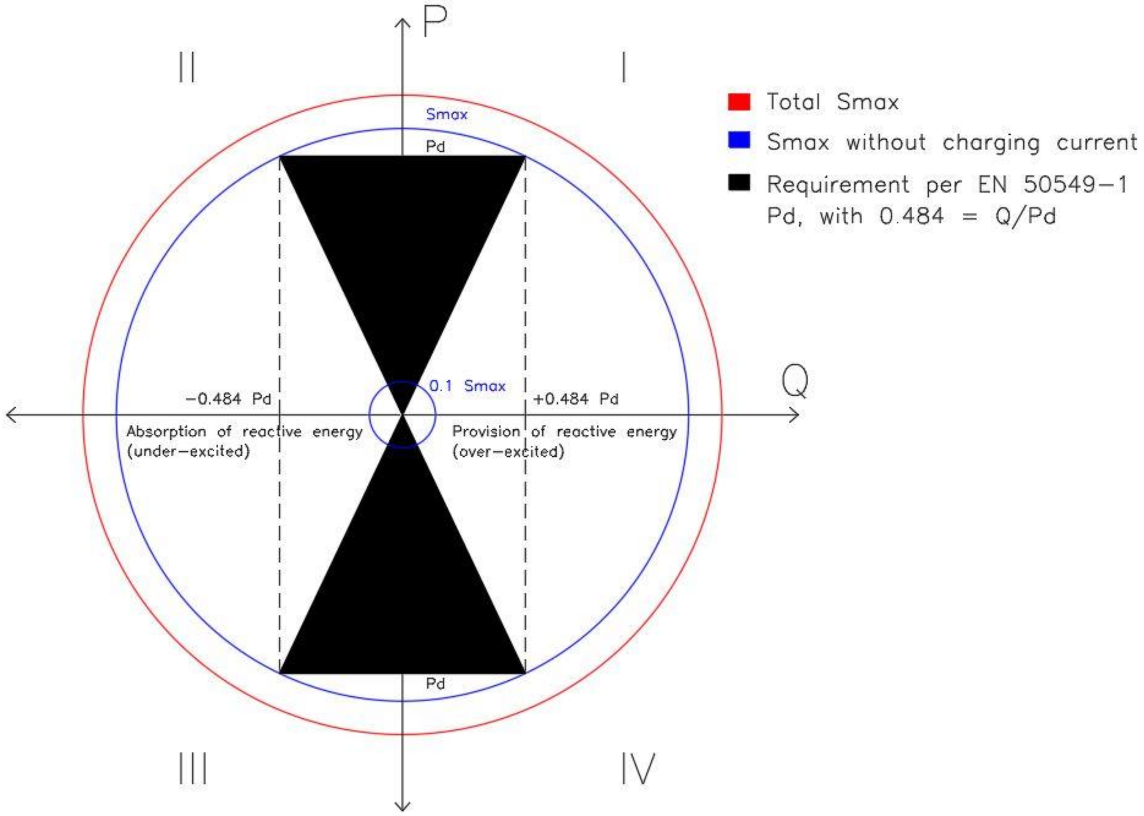

Figure 7. UPS input PQ-diagram with design active power (P_D). UPS is a generating module within a plant connected to a LV distribution network.

In Fig. 7, PQ-diagram is divided here to four quadrants based on the operation of the UPS. Quadrants I and II present the supply of active power to the grid side. Such operation could be utilized by “UPS as a Reserve”-application e.g., in which the active power will be drawn from the batteries for frequency containment reserve -markets [14]. It includes reactive power absorption and provision as per the requirements of the operational capabilities. For this thesis, the quadrants I and II are mirrored as quadrants III and IV. The UPS is operating in a normal mode (double conversion) while the active power is drawn from the supply grid as (-P). Based on the UPS’s input consumption, in this thesis RP can be injected to the supply side until the stated maximum input apparent power level is reached.

3.3 Generating plant MV-connection

European Standard EN 50549-2:2019 covers requirements for generating plants up to type B and included, which are to be connected in parallel to a MV distribution networks. The following mentioned notes are considered in this thesis as additional requirements, when comparing to LV-connected generating plants [15]:

- Unless stated otherwise by the DSO or the responsible party, the default RP requirement is up to 33 % of P_D over-excited and under-excited, when active power is above 20 % of P_D
- The operation below 20 % of P_D shall be provided to a minimum active factor of 0.52
- The RP capability is evaluated at the terminals of the each generating unit or at the POC
- The RP capability above power threshold P_D can be defined by the DSO and responsible party

The above notes are default minimum requirements. These requirements are shown as a grey area in the below Fig. 8 and are combined with the LV-connection requirements. The standard introduces also more stringent requirements, but only the default operational capability is included here.

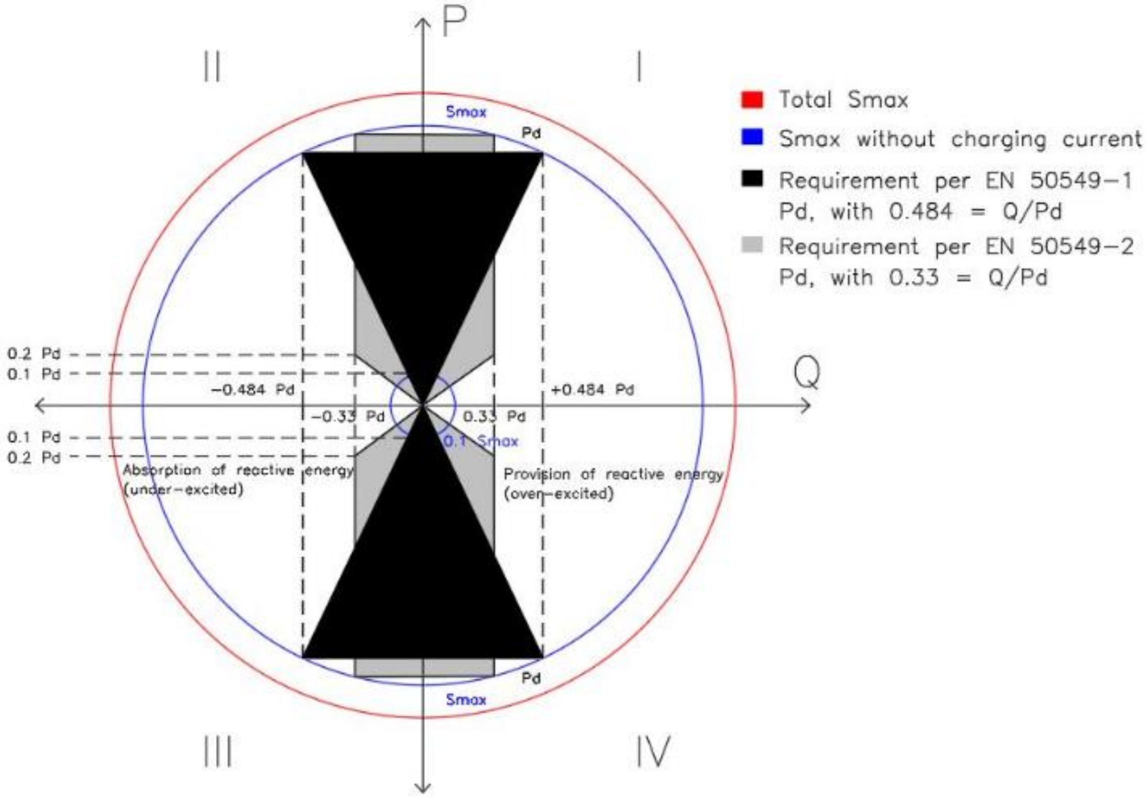

Figure 8. UPS input PQ-diagrams combined. UPS is a generating module within a plant connected to either LV or MV distribution networks.

For both connections, the product documentation showing the operation of the generating units are expected to have PQ-diagrams included. Additional requirements for continuous Var compensation can be involved by the generating plant, if agreed by the DSO and the producer. [15]. In Figures 7-8, such involvement can be covered while the above capabilities, design active power P_D and the technical limitations of the UPS are taken to account. These are combined in the following chapter for the UPS control method.

3.4 UPS control method

The requirements which were shown in the previous chapters for EESS apply during the normal operation of the generating units. It is also stated that the provisions apply to EESS in a generation mode. In the charging mode they should have the same characteristics. [13]. This has been noted for the UPS by a blue circle shown in Figures 7-8. Maximum compensation limit is then the nominal apparent power of the UPS. This allows the compensation characteristics to be fulfilled despite of the battery state-of-charge. Additionally, the provisions get fulfilled for the design active power and to its related RP levels.

Design active power P_D-limit is defined here by the nominal apparent power S_{max}. To fulfill both connection requirements shown in Fig. 8, the higher P_D-value of the MV-connection will be included in below Eq. (1). During the normal operation of the UPS, the RP generation mode can be applied when the following terms are true in sinusoidal conditions:

$$RP\ gen_{mode} \begin{cases} P_D = 0{,}95 * S_{max} \\ P_{input} \leq P_D \\ Q_{setpoint} \leq \sqrt{S_{max}^2 - P_{input}^2} \end{cases} \tag{1}$$

where

P_{input}	UPS normal operation active input power drawn for its end loads and battery charging
$Q_{setpoint}$	Requested setpoint for the reactive power injection

When operating above the S_{min}, which is shown as 0.1 S_{max} in Fig. 8, the following notes apply:

- S_{min} is 10 % of the S_{max} or 10 % of the generating plant's minimum regulating level (whichever is the higher value)
- The static accuracy of the RP capability needs to be $\pm$ 2 % of S_{max}
- Q setpoint –control method; response time for a new remote setpoint command needs to be less than one minute

Below the S_{min}-threshold, the deviations higher than 2 % are permissible, but requires to be as accurate as technically feasible. Although, it is stated in the standards that the exchange of un-controlled reactive power within this threshold cannot reach 10 % of the S_{max}. [13, 15]. The lowest possible limit for the compensation needs to be then evaluated that the above mentions can be fulfilled. Some limitations regarding the reactive power might arise with passive filtering components, as their effect might be bigger when the active power gets relatively small. According to Eq. (1), S_{max}-threshold could be even wider until the corresponding (P_D)-level is reached within the active power -axis. However, if it will be optimized closer to the total maximum apparent power -limitation shown as a red circle in Figures 7-8, rapid load level changes and the battery charging current require further evaluation to avoid any input overload triggering. If such triggering would occur, the UPS would transfer to batteries.

It is stated that if no or less than 0,33 Q/P_D or 0,484 Q/P_D -reactive power is required, the active power might increase above P_D. Also, the reactive power at active power levels below P_D might be lower when respecting the above referenced requirements. [13, 15].

3.5 Remote control and monitoring

In the previous chapter, Q setpoint -control method was chosen. Only one control method can be active at a time. Its configuration, activation and de-activation should be field-adjustable, remotely accessible and included in a product documentation. Depending of the power thresholds of the generating plants and if determined by the DSO, plant's operation and control parameters should be delivered for monitoring by the DSO- or/and the TSO-control centers. Such communication and monitoring should not directly interact with the power generating equipment, but with the operation of the plant. [15]. These guidelines are followed in the below example Fig. 9:

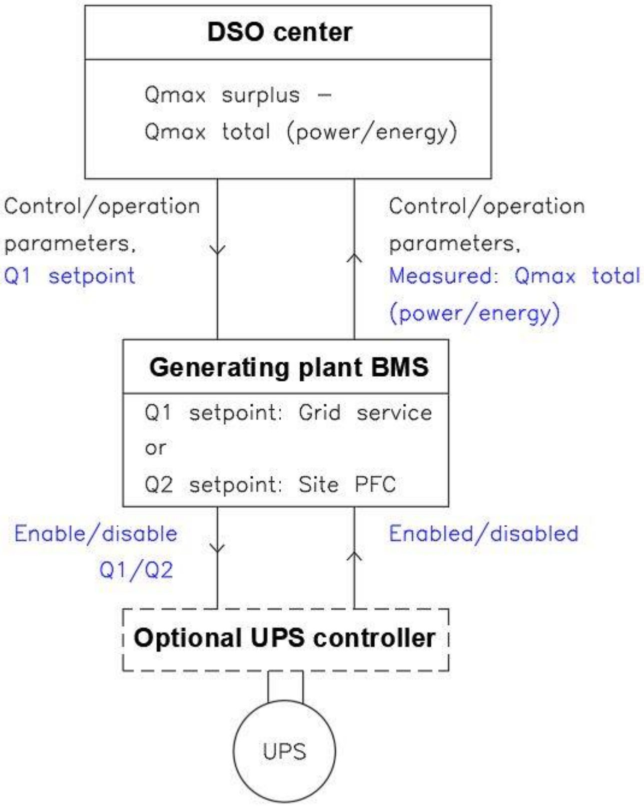

Figure 9. Principle of the remote communication between the DSO center, the generating plant BMS and the UPS.

In the Fig. 9, DSO center provides the request for the additional RPC as a Q1 setpoint -value to the generating plant’s BMS (building management system). When agreed, and if the UPS conditions allow as stated in Eq. (1), the generating plant can enable the UPS to provide such compensation for grid service. Optionally, generating plants can utilize UPS for the PFC within the site with a Q2 setpoint -value. These setpoints are separated here for clarification of the two theoretical approaches. Optional UPS controller can be utilized for controlling and monitoring. The UPS or its controller sends the status information to the

BMS. The total kvar-related energy- and power measurement data are monitored by the DSO via the kWh-meters at the POC.

3.6 UPS supply voltage fluctuations

The purpose of this chapter is to evaluate the difference in the UPS supply voltage when the RP injections takes place. In the below Table 1 is shown the technical variables used within this chapter.

Table 1. Technical variables utilized for the voltage fluctuation analyses.

Symbol	Description
P_{input}	Drawn UPS input active power [kW]
S_{input}	Drawn UPS input apparent power [kvar]
S_{max}	UPS nominal input apparent power without charging current [kVA]
P_{max}	UPS maximum input active power [kW]
Q_{max}	UPM maximum input reactive power [kvar]
U_s	Rated UPS input voltage (L-L) [V]
I_{ph}	Phase RMS supply current [A]
I_{max}	Phase max. RMS supply current [A]
$\cos(\varphi)$	Displacement power factor
r_{ph}	Phase resistance for cable [Ω/km]
x_{ph}	Phase reactance for cable [Ω/km]
S_n	Transformer nominal apparent power [kVA]
R_t	Transformer’s resistance at the secondary side [Ω]
X_t	Transformer’s reactance at the secondary side [Ω]
l	length of the supply cable [m]

To define the total voltage drop or increase during the UPS RP operations, isolating Dyn11-input transformer and supply cables impedances are summarized. An example schematic diagram is shown in below Fig. 10 for the voltage fluctuation analyses.

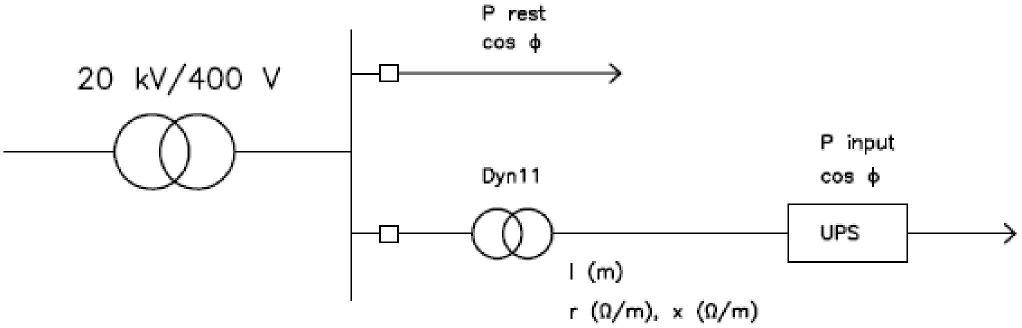

Figure 10. An example site schematic for the voltage fluctuation analyses.

Voltage drop in the transformer is calculated here with its type plate impedance-calculations shown in Table 2.

Table 2. Transformer impedance calculations.

Relative shortcut resistance	$r_k = \frac{P_k}{S_n}$
Relative shortcut reactance	$x_k = \sqrt{z_k^2 - r_k^2}$
Transformer’s secondary resistance	$R_t = r_k * \frac{{U_s}^2}{S_n}$
Transformer’s secondary reactance	$X_t = x_k * \frac{{U_s}^2}{S_n}$
Transformer secondary impedance with u_k	$Z_t = u_k * \frac{{U_s}^2}{S_n}$

In the Table 2, U_s presents the transformer’s secondary voltage too. Phase RMS (root mean square) supply current drawn by the UPS is:

$$I_{ph} = \frac{P_{input}}{\sqrt{3}U_s * \cos(\varphi)} \tag{2}$$

The total voltage drop is defined:

$$U_{drop} = \sqrt{3}U_{phdrop} \tag{3}$$

$$U_{phdrop} = I_{ph}[(R_t + r_{ph} * l) * \cos(\varphi) + (X_t + x_{ph} * l) * \sin(\varphi)] \tag{4}$$

Eq. (4) impedances are limited to consist of the isolating input transformer and the UPS supply cables.

Three UPS units with power ratings of 50 kW, 200 kW, 400 kW and accordingly three types of isolating Dyn11 -input transformers will be evaluated to see how the UPS input voltage depends of the RP injection. These will be compared to the default situation, in which the UPS rectifier is operating near unity power factor. Transformers can be sized based on the UPS maximum rectifier input currents shown in Appendices 2-3:

$$P_{max} = \sqrt{3}U_s * I_{max} \tag{5}$$

In addition to Eq. (5), the next available nominal apparent power level is chosen. In the below Tables 3-4, all system types are summarized for cable lengths 10 m, 20 m, 50 m, between the isolating transformer and the UPS. Supply cable multi-core sizes are chosen here based on the minimum recommendations in the user’s and installation guides for the rectifier inputs respectively [5, 16].

Table 3. Voltage fluctuations with lagging power factor.

UPS	**50 kW**	**200 kW**	**400 kW**
Multi-core cable size per phase	35 mm^2	240 mm^2	2*240 mm^2
Approximate cable properties [20]	MCMK 4x35/16 AN 1 kV;	MCMK 4x240/120 AN 1 kV	MCMK 2*(4x240/120 AN 1 kV)
AC resistance of phase and neutral + 70 °C conductor (Ω/km);	0,63;	0,097;	0,097;
Reactance: inductance (mH/km)/1000 *2*π*50 Hz (Ω/km)	0,085	0,082	0,082
External input transformer properties [21]	T3P0080K, S_n = 80 kVA, $z_k = 4\ \%$	T3P0315K, S_n = 315 kVA, $z_k = 4\ \%$	T3P0630K, S_n = 630 kVA, $z_k = 4\ \%$
P_k = Transformer load losses	$P_k = 1750\ W$	$P_k = 4400\ W$	$P_k = 6800\ W$
UPS nominal input apparent power S_{max} without charging current	52 kVA	209 kVA	420 kVA
Relative voltage fluctuations (%) per cable lengths 10 m, 20 m, 50 m with UPS lagging power factor;	$U_s = U_{busbar} - U_{drop}$ $\left(\frac{U_s}{U_{busbar}}\right) * 100\ \% -$ $100\ \% =$		
$\boldsymbol{\cos(\varphi) = 0,99}$	**-1.9; -2.1; -2.7**	**-1.4; -1.5; -2**	**-0.7; -0.8; -1.2**
$\cos(\varphi) = 0{,}7$	-2.7; -2.9; -3.4	-2.6; -2.8; -3.3	-1.3; -1.5; -2
$\cos(\varphi) = 0{,}5$	-2.7; -2.8; -3.2	-2.8; -2.9; -3.4	-1.4; -1.6; -2.1
$\cos(\varphi) = 0{,}3$	-2.6; -2.7; -2.9	-2.8; -2.9; -3.4	-1.5; -1.6; -2
$\cos(\varphi) = 0{,}1$	-2.4; -2.4; -2.5	-2.7; -2.8; -3.2	-1.4; -1.6; -2

Table 4. Voltage fluctuations with leading power factor.

Relative voltage fluctuations (%) per cable lengths 10 m, 20 m, 50 m with UPS leading power factor;	**50 kW**	**200 kW**	**400 kW**
$\boldsymbol{\cos(\varphi) = 0,99}$	**-1.3; -1.5; -2.1**	**-0.7; -0.8; -1.1**	**-0.3; -0.4; -0.7**
$\cos(\varphi) = 0{,}7$	0.4; 0.3; -0.06	1.1; 1.1; 1.1	0.7; 0.6; 0.6
$\cos(\varphi) = 0{,}5$	1.1; 1; 0.8	1.7; 1.7; 1.8	1; 1; 1.1
$\cos(\varphi) = 0{,}3$	1.6; 1.6; 1.5	2.2; 2.2; 2.4	1.2; 1.2; 1.4
$\cos(\varphi) = 0{,}1$	2; 2; 2.1	2.5; 2.6; 2.9	1.3; 1.4; 1.7

The predefined method for transformer sizing concludes that in the Tables 3-4 they are oversized in comparison to the chosen UPS nominal powers. However, from the analyses point of view this allows the reactive part of the Eq. (4) to be more dominant over its resistive part. Also, multi-core sizes of the supply cables were fixed irrespective of their length. Their sizes can be expected to be corrected accordingly for the short circuit protection and voltage drop.

It can be concluded that when compared to the near unity power factor operation without the RP injection, the decreased power factors in Tables 3-4 has at its lowest 3-4 % difference to the nominal operation. The biggest difference is noted during the leading power factor operation in Table 4, in which the UPS relative input voltage rises over 400 V line-to-line. From the system normal operation point of view, it is stated in the Appendix 2 that the rectifier input has operational tolerance of the rated 400 V line-to-line -20 %/ 20 %, and the bypass input -10 %/ +10 %. Analyses show, that with the chosen example components the system stays within those tolerances during the RP injections. However, by referring to the stated continuous voltage requirements in the chapter 3, when generating power, the producer shall take these voltage fluctuations into account within the generating plant [13].

4 UPS EFFICIENCY MEASUREMENTS

According to IEC 62040-3 standard, the UPS efficiency measurements shall be performed with a reference test load of power factor 1. It needs to be adjustable for the UPS to deliver 25 %, 50 %, 75 % and 100 % of the active power that it is rated. [17]. Three measurements per load step and condition were taken for the 50 kW UPS-unit. All UPS sub-systems intended to be operational in normal mode are active. Rectifier and bypass supplies are connected to the common source and summarized for the input measurement. Batteries are not connected. Enough time is left to reach the steady state conditions prior to the three measurements. One single multi-channel power analyzer instrument is utilized to provide simultaneous measurements with fast serial sampling. Count of ten measurements and their averaging was selected from the power analyzer for each measurement.

Fig. 11 shows the measurement method in the PQ-diagram for the efficiency measurement points. At first, the UPS normal operation efficiency is measured. Then the reactive power will be injected for the leading and lagging power factors until the nominal input apparent power is reached. Stated input nominal apparent power (S_{max}) without the charging current was 52 kVA, as in Table 4. Appendix 1 shows the physical measurement points as red circles for the power analyzer. The shown external input transformer was not part of the measurement setup. The UPS was supplied from the grid consisting of the TN-S network.

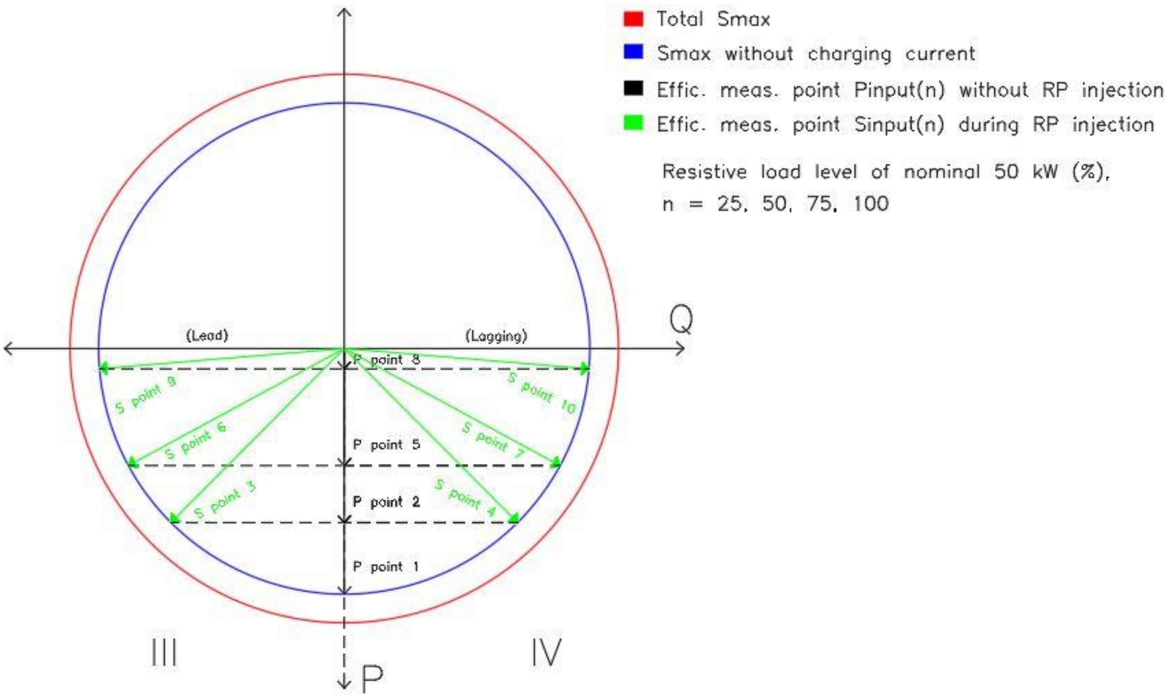

Figure 11. Measurement method shown in the PQ-diagram. Measurements will be taken without the RP injection for active powers (P point 1, P point 2...), and then with the RP injections for the apparent powers (S point 3, S point 4…) accordingly.

Resistive end load is used so that the measurements could be repeatable. The first measurement is taken with the nominal load 100 % without the RP injection. Then the following points will be measured based on the rated load levels of 50 kW: 75 %, 50 %, 25 %. The measurement results are plotted in Fig. 12. The resulting powers, efficiency average values (%) and error calculations with combined uncertainties ± (%) are presented in the Appendix 4 measurement template.

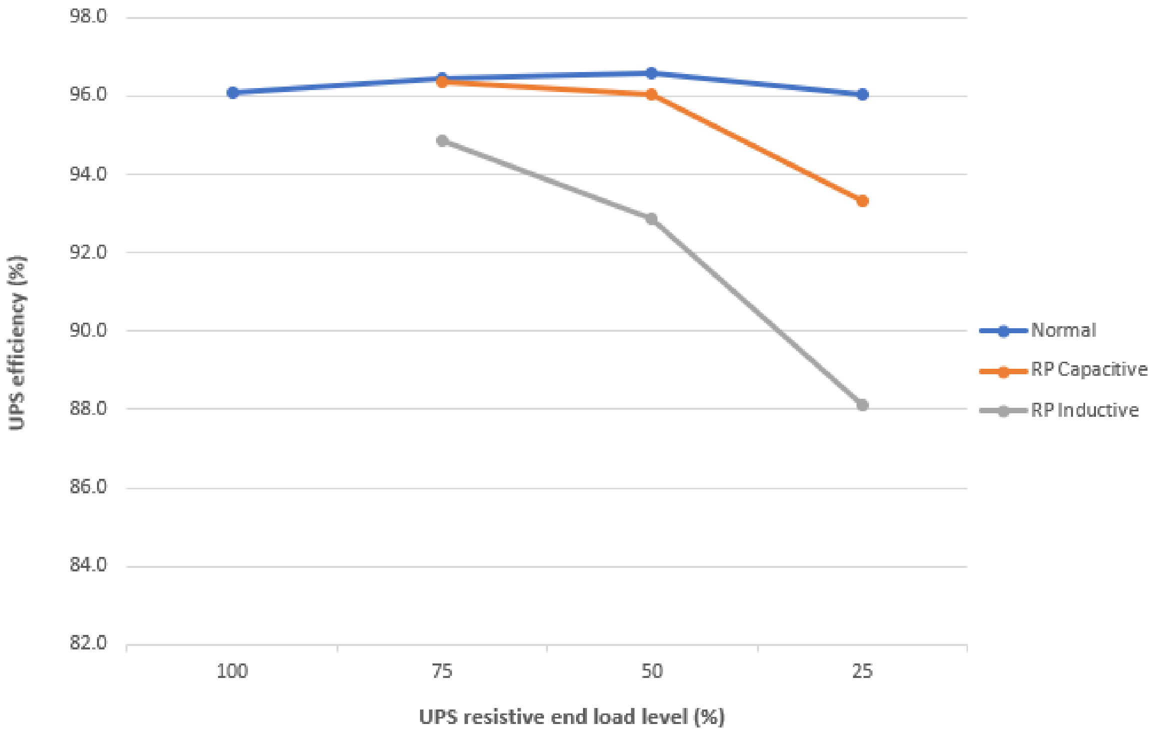

Figure 12. 50 kW UPS efficiency values plotted for normal, capacitive and inductive operation at 100 %, 75 %, 50 %, 25 % of its rated resistive load levels.

The measurement results in Fig. 12 show that the UPS efficiency drops during the both RP injections. Capacitive operation remains closer to the normal operation values. The inductive operation has the lowest efficiency value of 88.1 % with 25 % end load level. This value was recorded while the average total amount of injected RP was 42.8 kvar and the total apparent power only 45.1 kVA. The corresponding values for the capacitive operation were -50.2 kvar and 52 kVA. The minus sign refers to the leading power factor in the measurement data. The reason for the lower values during the inductive operation was the limitation of the RP capability during the programming phase. Injection commands were adjacent to the 50 kW -rating, and the system is more capacitive by its nature due to its capacitive filtering components. Their effect also increases when the drawn active power is lower. The inductive operation requires even more RP (more than 100 %) to be injected to reach the nominal apparent power. Accordingly, the efficiency value can be estimated to become lower than the recorded value of 88.1 %. The difference to normal operation efficiency would become then more than the current difference of 8 %. The capacitive operation has only 2.8 % difference to normal operation at its largest at 25 % load level. This can be concluded to be an incentive for a capacitive operation.

5 APPLICATION BUSINESS CASES

5.1 Grid-service

In this chapter two main theoretical approaches will be studied to form savings and costs of the RPC:

1. Diminishing surpluses of the reactive power content for the DSO
2. Power factor correction at the site

It is assumed here, that the generated reactive powers and the ones to be neglected are evenly distributed between the three phases in purely sinusoidal conditions with fundamental frequency.

The first one proposes that the UPS-operator would not have RP tariff-pricing involved due to adjusting their power factor for the DSO's favor. This kind of approach can be feasible e.g. for the data center operators which might not have additional loads connected in parallel to the UPS, while the site's power factor remains near unity by default. The second one is the site owner's specific optimization for the possible savings from the energy efficiency point of view or specific tariff. It would include kvar-based pricing and possible savings, when the RP level gets lower compared to the active power level. Such operators can correct their own PF due to capacitive or inductive loading at the UPS supply side.

In Finland, tariffs for RPC as grid-related tasks are given on a monthly basis tasks to distribution networks from the TSO Fingrid [1, 2]. These rules can create sanction fees, if there are too large surpluses of the reactive power content within the TSO connection points. Here it will be analyzed as a framework for annual hour services. The revenues are maximized, and the costs minimized over specific time period as stated in [1] for BESS in an energy system:

$$Profit_{application} = \int_{t=1}^{T} Revenue_{application}(t) - Cost_{application}(t)\, dt \qquad (6)$$

Here, we are only focusing on the RPC, but in the case of other applications like FCR, the above equation can be broken down into similar components. It is also stated that in the case of BESS, the value that grid-services provide to its operator depends of the following regardless of its type:

- "Economic regulations for that service (present fees or sanctions if not staying within the predefined limits)
- Cost of the devices installed in the grid providing that service: compensators, reactors, on-tap load changers
- Frequency of occurrence (how often the service should be provided) and cost of failure/damage that lack of service causes to the grid"

In the case of UPS, the following affect also to the availability of both approaches, but is not limited to:

- Supply grid disturbances (frequency of occurrence) causing UPS transferring to batteries (service disabled)
- UPS input or output load level changes
- Other site condition changes (parallel loading within supply transformer causing PQ-limitations, harmonics content causing PQ-limitations, site conditions causing UPS to transfer to its battery or static bypass)
- Generator supply connected (service disabled)
- Preventive maintenance work on the UPS (service disabled)

As an example, the application revenue can be determined by local grid's tariff charges and rewards achieved by eliminating excessive reactive content [1]. Here the application's profitable operation is then ensured, when the annual savings that the local grid receives are more than the annual costs of the UPS operation due the RP injection. RPC does not require use of batteries in the UPS. Also, during the double conversion mode, the reactive power content from its load side is not detected at its input side. The annual savings would need to be reasonably high for the DSO, while being profitable for the UPS-operator/owner who would act as a service provider:

$$S_{total} \geq Cost_{annual} \tag{7}$$

$$S_{total} = S_{RPC} \tag{8}$$

The total saving is consisting of the RPC only. The annual cost of the application is the combination of the investment cost and the operational cost:

$$Cost_{annual} = Cost_{investment} + Cost_{operation} \tag{9}$$

Annual investment cost is expressed by as a maximum reduced life-cycle of the UPM which participates to the RP injection, in comparison to its normal operation conditions:

$$\mathrm{Cost}_{\mathrm{max.investment}} = C2 - C1 \tag{10}$$

$$C1 = \frac{\mathrm{UPM}_{\mathrm{price}}}{\text{Lifetime (years) \%−load level}} \tag{11}$$

$$\mathrm{C2} = \frac{\mathrm{UPM}_{\mathrm{price}}}{\text{Reduced life time (years) \%−load level and full rect. operation}} \tag{12}$$

Eq. (11) assumes the life-cycle for the UPM in normal operation with predefined (%) load level of the nominal power and within specified environment conditions. Eq. (12) assumes the life-cycle for the UPM with predefined (%) load level of the nominal power in similar conditions, but also assumes that the rectifier would operate in full apparent power throughout the year during the reactive power injections. It is difficult to estimate accurately the lifecycle or degradation rate of the UPM. Although, with the stated assumptions, Eq. (12) would rather give higher investment cost estimation than lesser based on the application's real utilization hours. Also, the load level might increase or variate to be higher within the lifetime of the UPM, which would also affect to the max. investment cost when the UPS normal operation is compared to its RP injection. With it, the estimated annual investment cost is more feasible from the application-viability analyses point of view. However, this is not further studied within the scope of this thesis.

Annual operational cost is formed by the decrease in site efficiency due to increased reactive power consumption. It is compared to the default state of the site as shown below:

$$Cost_{operation} = \Delta P_{RP} * N_{injections} * Cost_{electricity}\left(\frac{€}{kWh}\right) * \left(\eta_{site_{normal}} - \eta_{site_{RP}}\right) + 12\ (months) * Cost(P_{max}) * \left(P_{max_{RP}} - P_{max_{normal}}\right) \tag{13}$$

where

C1	Normal operation calendar-aging-based annual cost of use [€], for assumed predefined load operation of the UPS nominal power
C2	RP injection calendar-aging-based annual cost of use [€], for assumed nominal full apparent power rectifier operation with predefined (%) load operation of the UPS nominal power
Lifetime	The number of years equal to UPM lifetime in normal operation conditions with predefined load level
Reduced life time	The number of years equal to UPM lifetime during both normal operation with predefined load-level and RP-injection for the remaining input PQ-window
ΔP_{RP}	Total average active power during RP-injection hours [kW]
$N_{injections}$	Total annual hours of RP-injection utilization [h]
$Cost_{electricity}$	Cost of energy 0.073 [€/kWh]

$\eta_{site_{normal}}$	Site efficiency during the UPS normal operation for predefined load-level
$\eta_{site_{RP}}$	Site efficiency during UPS RP-injection for predefined load-level
$12\ (months)$	Monthly pricing
$Cost(P_{max})$	Cost of power 1.9 [€/kW]
$P_{max_{normal}}$	Total max. power during normal operation
$P_{max_{RP}}$	Total max. power during RP-injection

In Eq. (13), the reactive power consumed by the rectifier is seen as kWh -related power consumption increasement due to higher power dissipations within the site. It also includes the maximum active power related cost 1.9 €/kW. Inclusion is for the hypotheses that the injections are causing increasement to the monthly maximum active power when compared to the normal operation. Profitability is ensured when the RPC savings are higher than the above-mentioned costs. Annual total savings for the DSO is formed from Eq. (14):

$$S_{RPC} = Price(Q\ surplus) * (Q_{max}\ total) * 12\ (months) + Price(Q\ energy) * (Q_{max}\ total) * N_{injections} \tag{14}$$

where

$Price(Q\ surplus)$	Unit price per reactive power [€/kvar]
$(Q_{max}\ total)$	Total RP injected by the UPS [kvar], limited by the PQ window of the rectifier
$12\ (months)$	Monthly pricing
$Price(Q\ energy)$	Reactive energy fee [€/kvarh]
$N_{injections}$	Total annual hours of RP-injection utilization [h]

In Finland, the reactive power tariff introduced by TSO Fingrid in the beginning of 2017 concerns DSO companies 2019 onwards:

- Reactive power exceeding PQ -limits, a unit price of 1000 €/Mvar, month
- Reactive energy fee of 5 €/Mvarh when PQ -limits exceeded

Tariff also allows to eliminate 50 highest reactive power peaks per month. [1, 2]. There is no clear reward mechanism associated for the grid-related services, but the UPS -owner would need to maximize profit as a service provider for RP capacity. The above calculations are utilized to form savings and costs in the chapter 6.1.

5.2 Power factor correction

In the second part of the theoretical approaches, increasing the site's power factor is expected to have an efficiency improvement. It would also attempt to neglect the site's kvar-based pricing, if the PQ -requirements due to excessive reactive power are not met. Investment cost shown in Eq. 10-12 applies here with exception, that the UPS does not necessarily require full rectifier operation based on the site's own reactive power levels. Also, it could be expected to have more adaptive operation requirements based on the frequency of changes that the parallel loading causes to the UPS supply side.

Due to site's efficiency improvement expectations, Eq. (13) will be tuned to form an annual operational cost in case the site's efficiency decreases:

$$Cost_{operation2} = \Delta P_{RP} * N_{injections} * Cost_{electricity}\left(\frac{€}{kWh}\right) * \left(\eta_{site_{RP}} - \eta_{site_{normal}}\right) \tag{15}$$

In case the site efficiency increases during the RP injections, Eq. (15) forms additional savings. It does not include monthly active power fee, because the maximum power is not expected to increase when compared to the unity power factor operations of both the UPS and the parallel load. The annual cost of the application needs to be covered here by savings to the site owner. Total savings is formed:

$$S_{RPC2} = Price(Q\ power) * Q_{power}\ (total) * 12\ (months) \tag{16}$$

where

$Price(Q\ power)$	Reactive power fee [€/kvar]
$Q_{power}\ (total)$	Total average reactive power neglected by the UPS [kvar] during the hourly injections
$12\ (months)$	Monthly pricing
ΔP_{RP}	Total average active power during the RP -injection hours [kW]
$N_{injections}$	Total annual hours of the RP -injection utilization [h]
$Cost_{electricity}$	Cost of energy 0.073 [€/kWh]
$\eta_{site_{normal}}$	Site efficiency during the UPS normal operation for predefined load-level
$\eta_{site_{RP}}$	Site efficiency during the UPS RP -injection for predefined load-level

The reactive power tariff will be chosen here based on the example for MV -connected industrial customers in Finland Espoo region [18]. The tariff pricing concern customers whose monthly maximum reactive power is more than 20 % of the corresponding monthly maximum active power:

- Reactive power fee of 4,05 €/kvar, month, inductive and capacitive

The corresponding limit can be expressed as a power factor of 0,98. In Finland, the tariff changes based on the local DSOs. In some regions, the capacitive RP can be more restricted having 5 % limit to the reference maximum active powers, and the pricing compared to inductive RP five times more [19].

6 SAVINGS AND COSTS

6.1 Grid service

The below Fig. 13 shows an example schematic diagram of the grid service analysis in three phase system. It consists of the 630 kVA MV -transformer, 2*240 mm^2 supply cables per phase, and the 400 kW -rated UPS having 420 kVA nominal input apparent power.

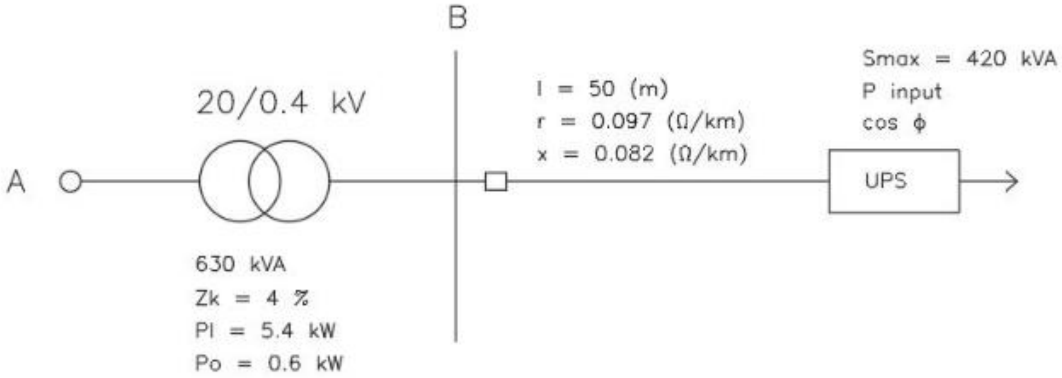

Figure 13. An example schematic diagram of the grid service analysis in three phase system. The analysis includes 630 kVA MV -transformer, 2*240 mm^2 supply cables per phase, and the 400 kW -rated UPS having 420 kVA nominal input apparent power. Listed cable properties concern each cable.

The parameters for the analysis are shown in below Tables 5-6.

Table 5. The parameters and their values for the grid service analyses.

UPS end load level %	UPS output power (load) kW	$\eta_{site_{normal}}$	$\eta_{site_{RP}}$		$P_{max_{RP}}$	
			capacitive operation	inductive operation	capacitive operation kW	inductive operation
75	301.9	0.9528	0.9447	0.9288	336.9	342.3
50	203.1	0.9560	0.9329	0.9002	233	240.9
25	99.9	0.9503	0.8818	0.8003	121.7	133.3

Table 6. The parameters and their values for the grid service analyses.

UPS end load level	UPS normal operation PF	UPS PF		$P_{max_{normal}}$	$Q_{max} total$	
	Leading	capacitive operation leading	inductive operation lagging		capacitive operation	inductive operation
%				kW	kvar	
75	0.9952	0.76	0.76	327.8	-273.9	273.9
50	0.9872	0.52	0.52	219.4	-360.4	360.4
25	0.9374	0.258	0.258	109.2	-407.9	407.9

Site efficiencies were calculated by the following equation:

$$\eta_{site} = \frac{P_{UPS\ output}}{TF_{load\ losses} + TF_{no\ load\ losses} + Cable_{losses} + UPS_{losses} + P_{UPS\ output}} \tag{17}$$

where

$P_{UPS\ output}$	UPS output power [kW]
$TF_{load\ losses}$	Transformer load losses [kW]
$TF_{no\ load\ losses}$	Transformer no-load losses [kW]
$Cable_{losses}$	Cable losses [kW]
UPS_{losses}	UPS losses [kW]

The following simplifications were included in the analysis:

- The measured efficiency values for 50 kW -unit in the chapter 4 are utilized for the 400 kW -unit here
- 400 kW -unit is consisting of eight similar internal power modules
- During the RP injections, the total UPS nominal apparent power is 420 kVA
- The efficiency value for the inductive operation at 25 % end load is estimated to be 85 % with a capability to supply 405.8 kvar RP
- Injected RPs during both operations were calculated with the same power factor values listed in the Table 6 (ref. to Appendix 4)

Also, the total reactive power consumed by the site consists of the UPS and its supply cables.

Annual total savings and cost of operation in chapter 5.1 are calculated and plotted. Sensitivity analyses were carried out with the total annual injection hours of 300 h, 2920 h and 5840 h for each of the resistive rated end load levels 75 %, 50 %, and 25 %. The capacitive operation annual total savings (€/a) and cost of its operation (€/a) are shown in Figures 14-16, and for the inductive operation accordingly in Figures 17-19.

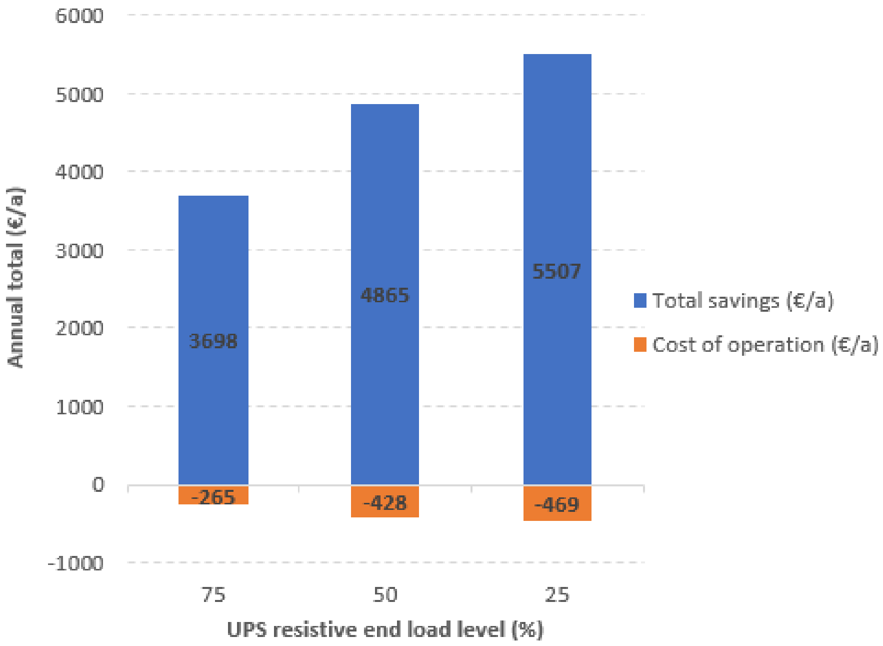

Figure 14. Capacitive operation total annual savings and cost (€/a) with the total annual injection hours of 300 (h/a) for the UPS rated end load levels (%).

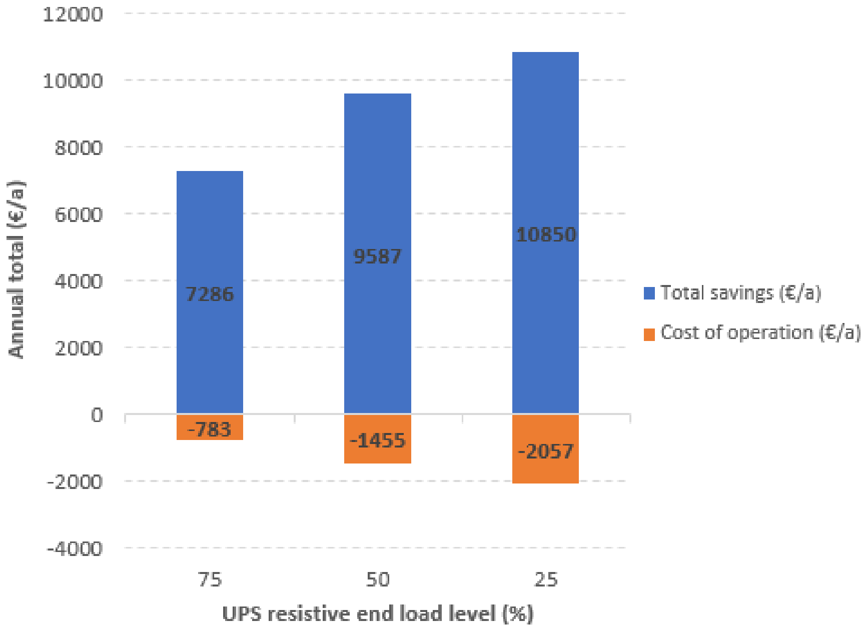

Figure 15. Capacitive operation total annual savings and cost (€/a) with the total annual injection hours of 2920 (h/a) for the UPS rated end load levels (%).

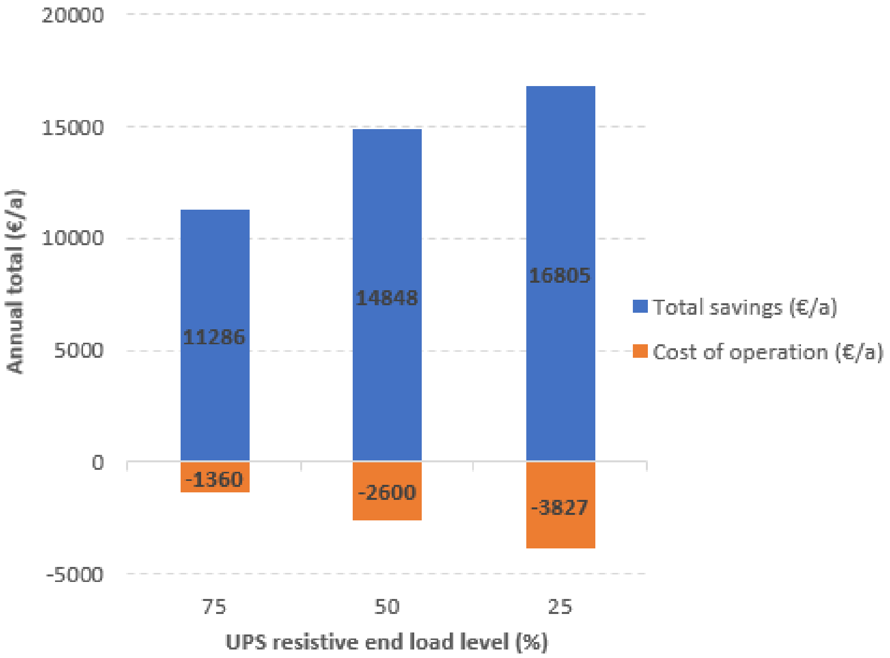

Figure 16. Total annual savings and cost (€/a) of the capacitive operation with the injection hours of 5840 (h) for the UPS rated end load levels (%).

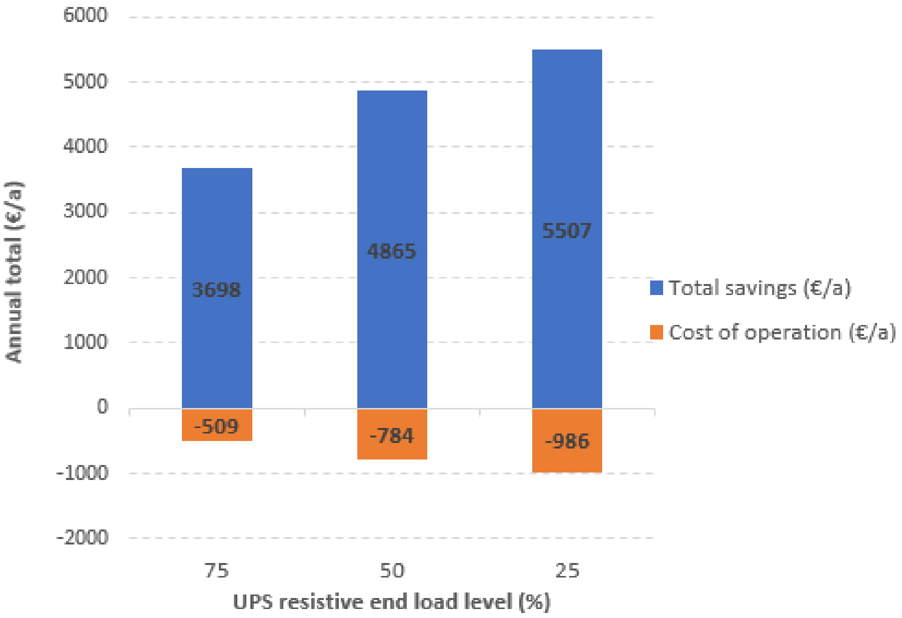

Figure 17. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 300 (h) for the UPS rated end load levels (%).

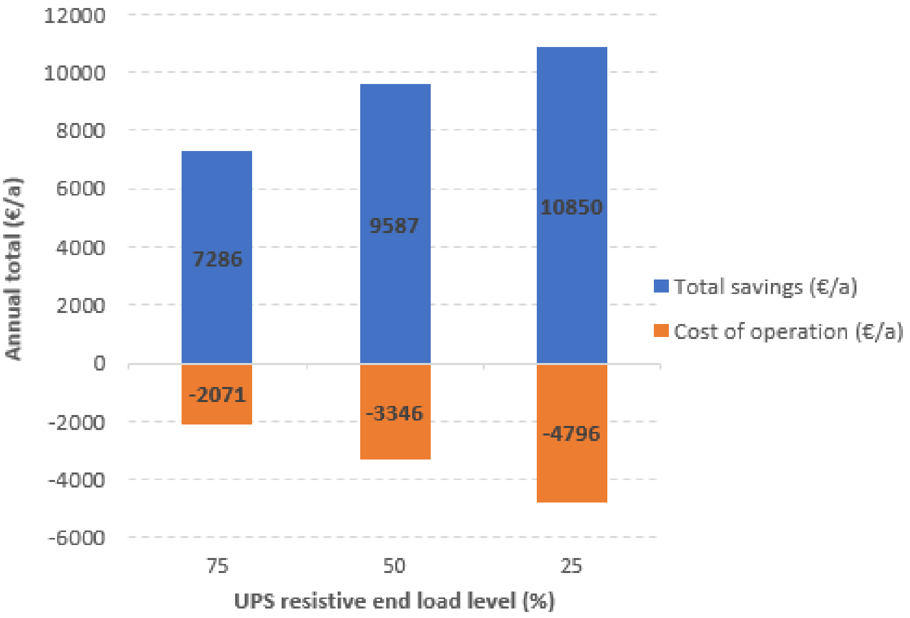

Figure 18. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 2920 (h) for the UPS rated end load levels (%).

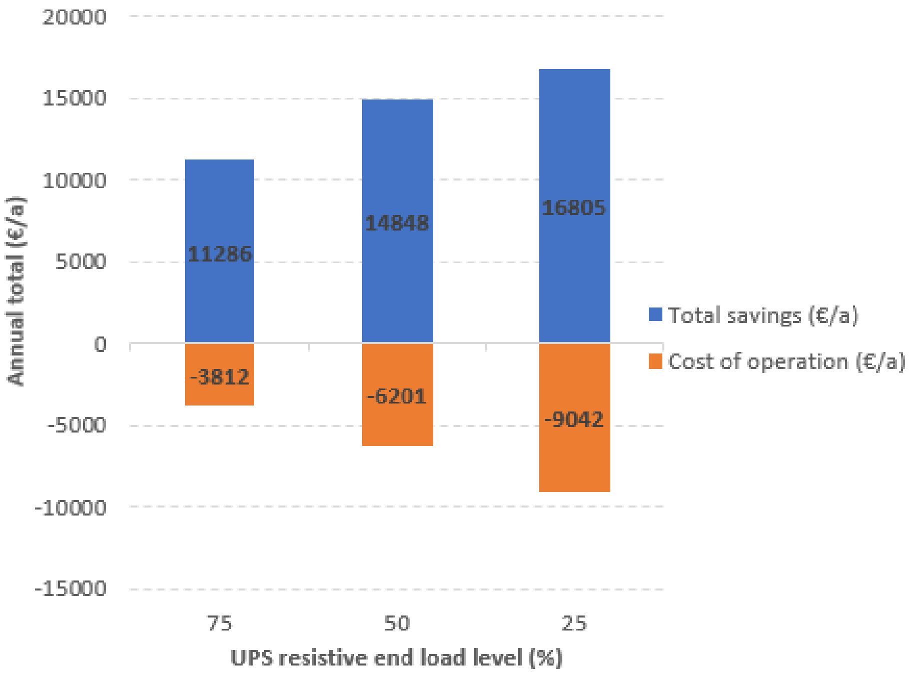

Figure 19. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 5840 (h) for the UPS rated end load levels (%).

It can be concluded from the analyses that the most profitable scenario for the capacitive operation can be achieved when the injection hours were 5850 h, and the rated load level 25 %. For the inductive operation, the most profitable scenario was during the same injection hours with 50 % rated load level.

6.2 Power factor correction

The below Fig. 20 shows an example schematic diagram of the PFC analysis. The local three phase system would consist of the 400 kVA MV -transformer, 240 mm^2 supply cables per phase for the parallel load having 200 kVA nominal input apparent power, and 35 mm^2 supply cables per phase for the 50 kW -rated UPS having 52 kVA nominal input apparent power.

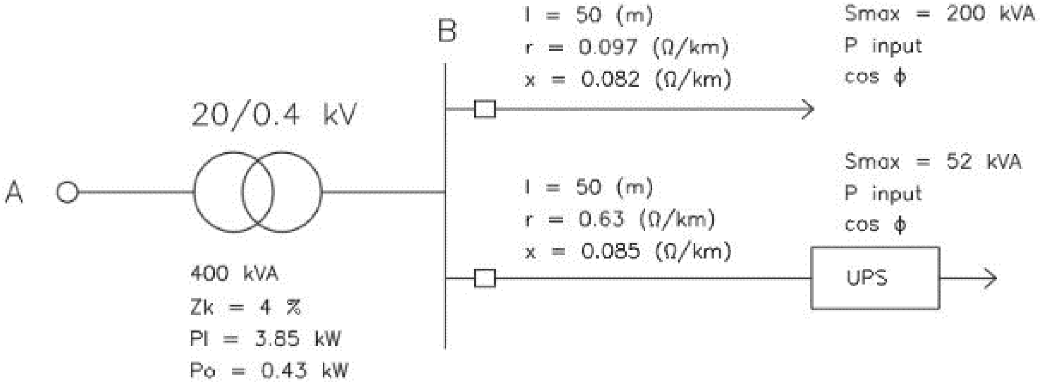

Figure 20. An example schematic diagram of the PFC analysis. The analysis includes 400 kVA MV -transformer, 240 mm^2 supply cables per phase for the parallel load having 200 kVA nominal input apparent power, and 35 mm^2 supply cables per phase for the 50 kW - rated UPS having 52 kVA nominal input apparent power. Listed cable properties concern each cable.

The required RP to be compensated by the UPS was calculated based on the tariff in chapter 5.2. The monthly maximum active power of the site is assumed to be present during the unity power factor operation of both the UPS and the parallel load. The allowable 20 % limits of the RP were then calculated, and the RP capacity of the UPS was summarized. This way the new power factors for the parallel load were evaluated for the analysis. Table 7 summarizes the compensation requirements for each rated load level of the UPS.

Table 7. Summarized parameters of the compensation requirements and their values.

UPS rated load level	Site's max. active power during unity power operation	Allowable 20 % reactive powers	UPS reactive power		Summarized RP	New lead/lagging PF for the parallel load
			capacitive operation	inductive operation		
%	kW	kvar	kvar		kvar	
75	242.5	48.5	-33.8	33.8	82.3	0.9114
50	229.3	45.9	-44.4	44.4	90.3	0.8923
25	215.8	43.2	-50.2	50.2	93.4	0.8843

Other parameters of the PFC analysis are shown in below Tables 8-9.

Table 8. Other parameters of the PFC analyses and their values.

UPS rated load level	UPS normal operation PF	UPS PF		ΔP_{RP}	$Q_{power} total$	
	Leading	capacitive operation leading	inductive operation lagging		During UPS capacitive operation	During UPS inductive operation
%				kW	kvar	
75	0.9952	0.76	0.76	225.3	30	37.7
50	0.9872	0.52	0.52	208.8	40.2	48.7
25	0.9374	0.258	0.258	193.4	45.5	55.1

Table 9. Other parameters of the PFC analyses and their values.

UPS rated load level	UPS output power (load)	$\eta_{site_{normal}}$		$\eta_{site_{RP}}$	
		When parallel PF lagging, UPS PF leading	When parallel PF leading, UPS PF leading	When parallel PF lagging, UPS PF leading	When parallel PF leading, UPS PF lagging
%	kW				
75	37.7	0.9789	0.9789	0.9780	0.9753
50	25.4	0.9811	0.9810	0.9789	0.9745
25	12.5	0.9829	0.9828	0.9789	0.9719

Site efficiencies were calculated by the following equation:

$$\eta_{site} = \frac{P_{UPS\ output} + P_{parallel}}{TF_{load\ losses} + TF_{no\ load\ losses} + UPS_{cable\ losses} + Parallel_{cable\ losses} + UPS_{losses} + P_{UPS\ output} + P_{parallel}} \quad (18)$$

where

$P_{UPS\ output}$	UPS output power [kW]
$P_{parallel}$	Parallel load power [kW]
$TF_{load\ losses}$	Transformer load losses [kW]
$TF_{no\ load\ losses}$	Transformer no-load losses [kW]
$Parallel_{Cable\ losses}$	Parallel load cable losses [kW]
$UPS_{Cable\ losses}$	UPS cable losses [kW]
UPS_{losses}	UPS losses [kW]

The following simplifications were included in the analysis:

- During the RP injections, the total UPS nominal apparent power is 52 kVA
- The efficiency value for the inductive operation at 25 % end load is estimated to be 85 % with a capability to supply 50.2 kvar reactive power
- Injected RPs during both operations were calculated with the same power factor values listed in the Table 8 (ref. to Appendix 4)

Also, the total compensating reactive power consists of the UPS and its supply cables. Although, the reactive power component of the cables is insignificant here (total < 100 var).

Annual total savings and cost of operation in chapter 5.2 are calculated and plotted. Sensitivity analyses were carried out with the total annual injection hours of 300 h, 2920 h and 5840 h for each of the resistive rated end load levels 75 %, 50 %, and 25 %. The capacitive operation annual total savings (€/a) and cost of its operation (€/a) are shown in Figures 21-23. Accordingly, for the inductive operation in Figures 24-26.

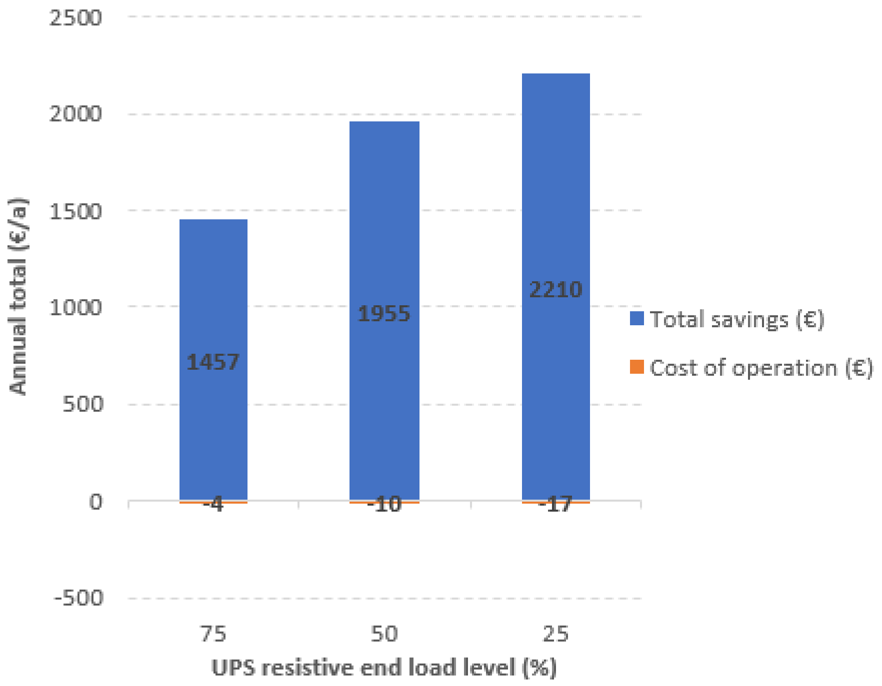

Figure 21. Capacitive operation total annual savings and cost (€/a) with the total annual injection hours of 300 (h/a) for the UPS rated end load levels (%).

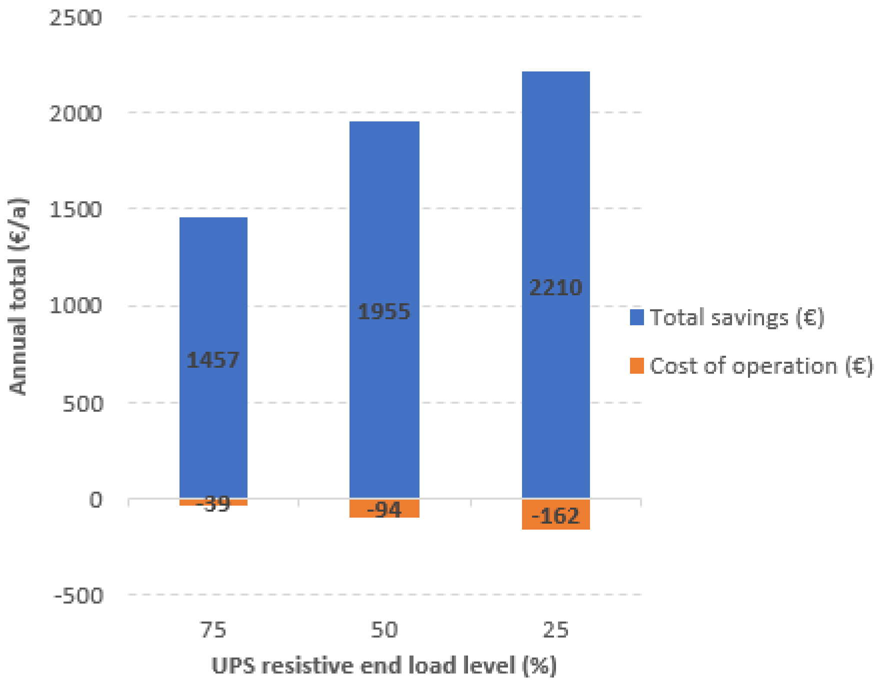

Figure 22. Capacitive operation total annual savings and cost (€/a) with the total annual injection hours of 2920 (h/a) for the UPS rated end load levels (%).

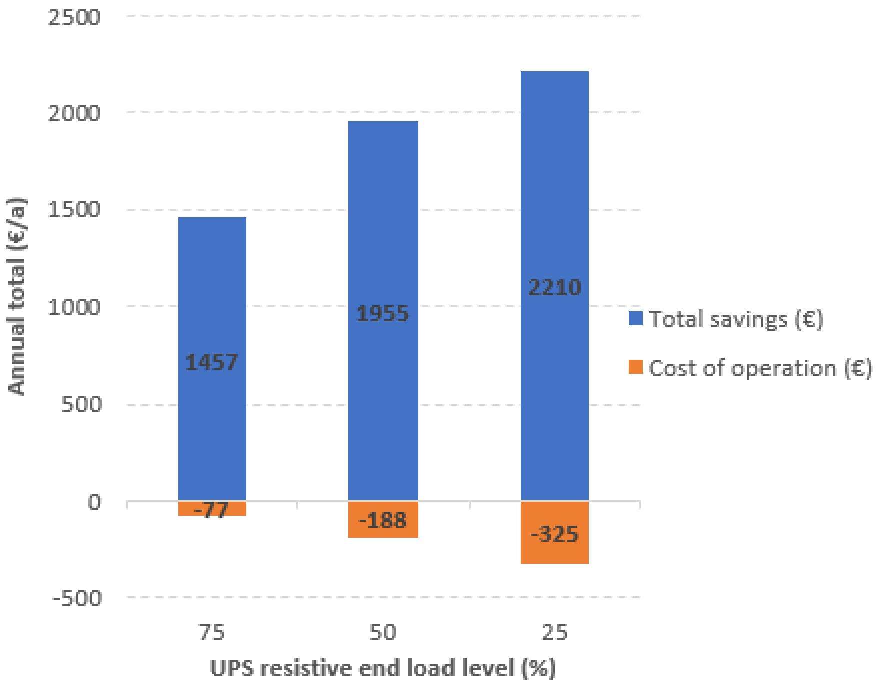

Figure 23. Total annual savings and cost (€/a) of the capacitive operation with the injection hours of 5840 (h) for the UPS rated end load levels (%).

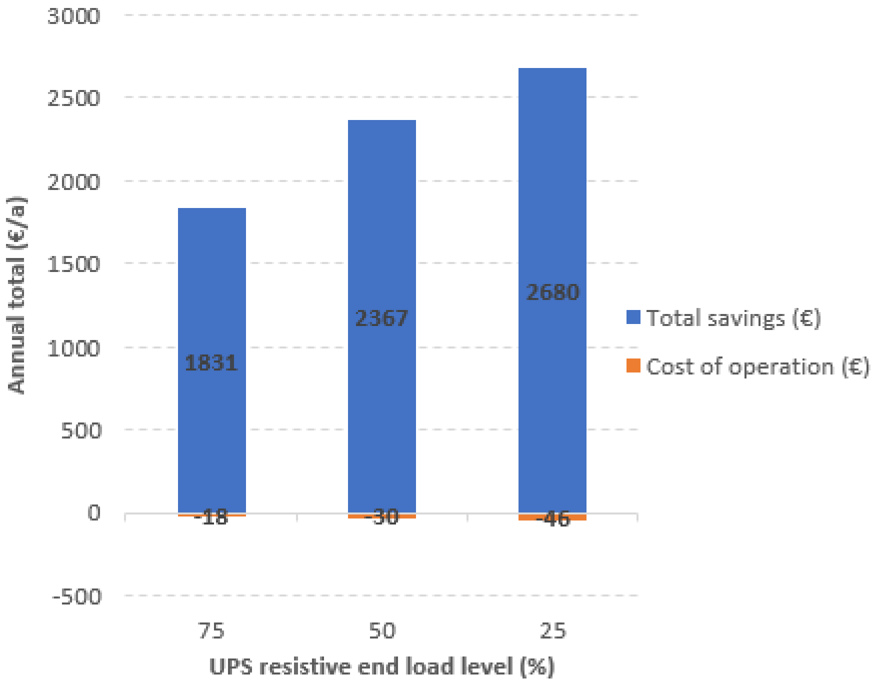

Figure 24. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 300 (h) for the UPS rated end load levels (%).

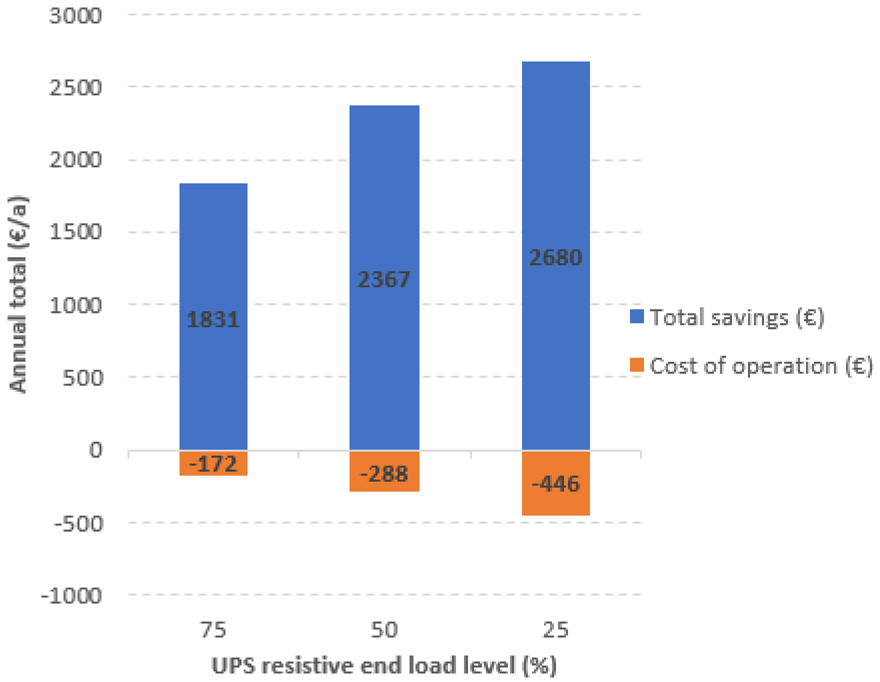

Figure 25. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 2920 (h) for the UPS rated end load levels (%).

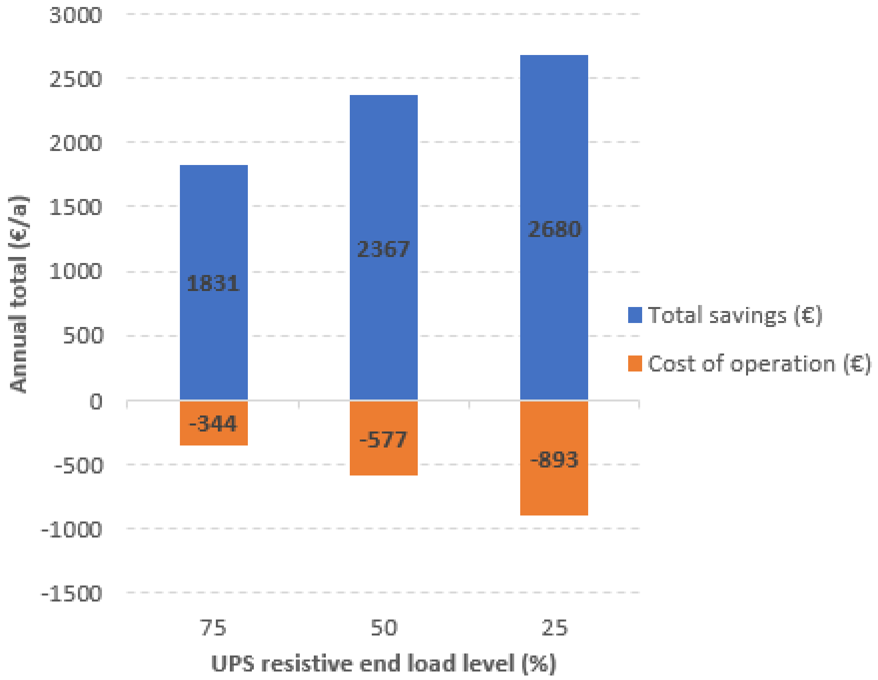

Figure 26. Total annual savings and costs (€/a) of the inductive operation with the injection hours of 5840 (h) for the UPS rated end load levels (%).

It can be concluded from the analyses that the most profitable scenario for the capacitive operation can be achieved when the injection hours were the least 300 h, and the rated load level 25 %. For the inductive operation, the most profitable scenario was during the same conditions.

7 RESULTS EVALUATION

7.1 Grid service

Savings and costs concluded in the previous chapter show that the both business cases are viable in all studied conditions. The maximum application revenues will be calculated during the most profitable conditions and compared to the RP capacity.

The grid service -related savings from the DSO’s perspective or income from the UPS operator’s perspective, are increasing with the injection hours. It’s active/reactive power related savings and costs are mostly effective during the low injection hours of 300 h. The reactive power energy -related component gets highly dominant during 2920 h and 5840 h annual injections, which are 1/3 and 2/3 portions of the annual total hours. The viability also increases in relation to the reactive power capacity when the rated load level is lower. However, exception to this occurs during the inductive operation between 2920-5840 h annual injections and 25-50 % rated load levels, as the 50 % rated load level has lesser losses with stated 92.9 % efficiency compared to the estimated 85 % efficiency. Due to electricity consumption the cost of operation becomes more dominant.

Calculated total reactive powers in Table 6 did consist of the supply cables and the UPS during its nominal apparent 420 kVA. During the maximum injection with the 0.258 leading/lagging PF, its supply cables consumed reactive power component of 2.1 kvar leading/lagging. The UPS RP capacity itself was then 405.8 kvar lead/lagging. Accordingly, during the inductive operation at most favorable 50 % rated load level condition and with the power factor of 0.52 leading/lagging, the corresponding values were 1.6 kvar and 358.8 kvar. The maximum revenues in the most profitable conditions will be divided with the total RP consumed by the site below:

Capacitive operation with 5840 h annual injections and 25 % rated load level, 400 kW -unit with 405.8 kvar leading RP capability:

- Max. application unit revenue 31.8 €/kvar, a

Inductive operation with 5840 h annual injections and 50 % rated load level, 400 kW unit with 358.8 kvar lagging RP capability:

- Max. application unit revenue 24 €/kvar, a

By referring to the chapter 5.1, application to be profitable for the DSO and the unit owner, these can also be defined as break-even points when compared to any associated external investment cost with the degradation rate of power electronics.

7.2 Power factor correction

The total savings achieved from the PFC were independent of the annual injection hours due to monthly reactive power pricing. Compensation requires to occur at least once per month to avoid the monthly reactive power peak. The maximum application revenue can be concluded to occur with the least injections as possible, while the parallel loading has the lowest power factor. Accordingly, the UPS would have the highest RP capacity with 25 % rated load level. However, exception to this occurred during the inductive operation between 25-50 % load levels with annual injection hours of 5840 h. During then, the cost of operation with increased consumption was relatively large compared to the savings. The measured unit is capacitive by its nature due to filtering capacitors. Therefore, the inductive operation creates higher savings with the increased demand of RP capacity, when the parallel load has leading power factor too.

In general, the cost of operation did increase with the injection hours due to increased consumption. Also, the site efficiencies maintained to decrease compared to the normal state efficiencies.

Total RP neglected by the UPS were shown in Table 8. The maximum revenues in the most profitable conditions will be divided with those values:

Capacitive operation with 300 h annual injections, 25 % rated load level, 50 kW -unit with -50.2 kvar leading RP capability, and the parallel load power factor is 0.88 lagging:

- Max. application per unit revenue 48.2 €/kvar, a

Inductive operation with 300 h annual injections, 25 % rated load level, 50 kW -unit with 50.2 kvar lagging RP capability, and the parallel load power factor is 0.88 leading:

- Max. application per unit revenue 47.8 €/kvar, a

By referring to the chapter 5.1, these can also be defined as break-even points when compared to any associated external investment cost with the degradation rate of the power electronics.

8 CONCLUSION AND FUTURE STUDIES

The objective of this thesis was to study the viability of reactive power compensation with the double conversion UPS. This was conducted by the efficiency measurements for the 50 kW rated UPS, and the information was utilized in two theoretical business case analyses. The reactive power capability was limited to the nominal apparent PQ -window of the UPS rectifier.

The measurements of the unit showed that during the capacitive operation, the system efficiency remains better than during the inductive operation. Both operations show higher losses compared to the normal operation. The biggest difference between the two operations was noted during the 25 % of the rated load level, when the capability to inject reactive power was largest until the stated nominal apparent power was reached. The capacitive operation had then 2.8 % difference to the normal state efficiency, as where the inductive operation had 8 % difference. During the measurements it was noted however, that the reactive power capability during the inductive operation were falling to 42.8 kvar lagging. Whereas, the capacitive operation had 50.2 kvar leading reactive power. Reason for this was noted by the increasing effect of the input capacitive filtering components when the drawn active power is lower. The commands were programmed and limited according to the unit rating and should have been further increased for the inductive operation. Due to this, the inductive operation was estimated to have 85 % efficiency for the 25 % rated load level in the analyses. Also, for simplicity, the theoretical analyses were calculated by the same power factors for both operations. This is estimated to cause some deviation to final reactive power capabilities. Other stated efficiency values were counted from the measurements.

Theoretical analyses showed that the both cases have income possibilities. The annual per unit revenues (€/kvar, a) were concluded during the inductive and capacitive operation. Offering the reactive power capacity for a local site compensation had larger values. However, its utilization was greatly restricted based on the demand compared to the parallel load power factor and the monthly based tariff. The power factor of the 200 kVA parallel load was calculated to variate between 0.88 leading/lagging. Offering the reactive power to the local DSO had great incentives from the reactive energy point of view of the tariff. This creates incentive for the service provider to enlarge the current system redundancy and allow its operation as many annual hours as technically feasible based on the demand. Also, from the additional savings and power quality point of view, if the legislation allows, DSOs could utilize themselves such capability within microgrids or by widely distributed energy storage units near end customers. In the most favorable conditions, the annual unit revenues were within 24-48.2 €/kvar, a. The results did not include any additional investment cost or degradation rate of the power electronics. Evaluation of those would determine more accurately the final profitability of the cases. The possibility to program the existing bidirectional rectifier for such operation assumes though that such implementation can be cost-effective and competitive. Evaluation of these results and comparison to other available solutions, the overall market-viability can be analyzed.

Future studies could consist of measuring the efficiencies and capabilities for the larger frame UPSs. Within this thesis there was an estimation conducted based on the measured 50 kW -unit for the studied 400 kW -unit. Even though the units can consist of similar internal power modules. Also, the power losses and temperatures regarding the components in the rectifier needs to be validated precisely during the injections. This was not included within the scope of thesis. Such validation would exactly conclude the component stresses and the maximum reactive power operation.

One possibility to increase the maximum power of the rectifier could be the utilization of the active NPC -topology with two additional IGBTs per phase leg for its neutral connection. With the temperature analyses, power losses between the components could be then balanced out. This does not however improve the overall efficiency. [7].

The efficiency of the inductive operation could be studied and improved in the future. Incentives for that are the increasing amount of underground cables causing capacitive RP with a new infrastructure [3]. In general, the system feature suitability for dynamic conditions is technically feasible based on the early testing and by referring to the standards. Although, it requires further validation based on the real environment conditions. Also, harmonics are involved, and their relation to the studied fundamental frequency compensation needs to be analyzed. All things considered, the UPS needs to operate as intended for the protection of its critical loads without interruptions.

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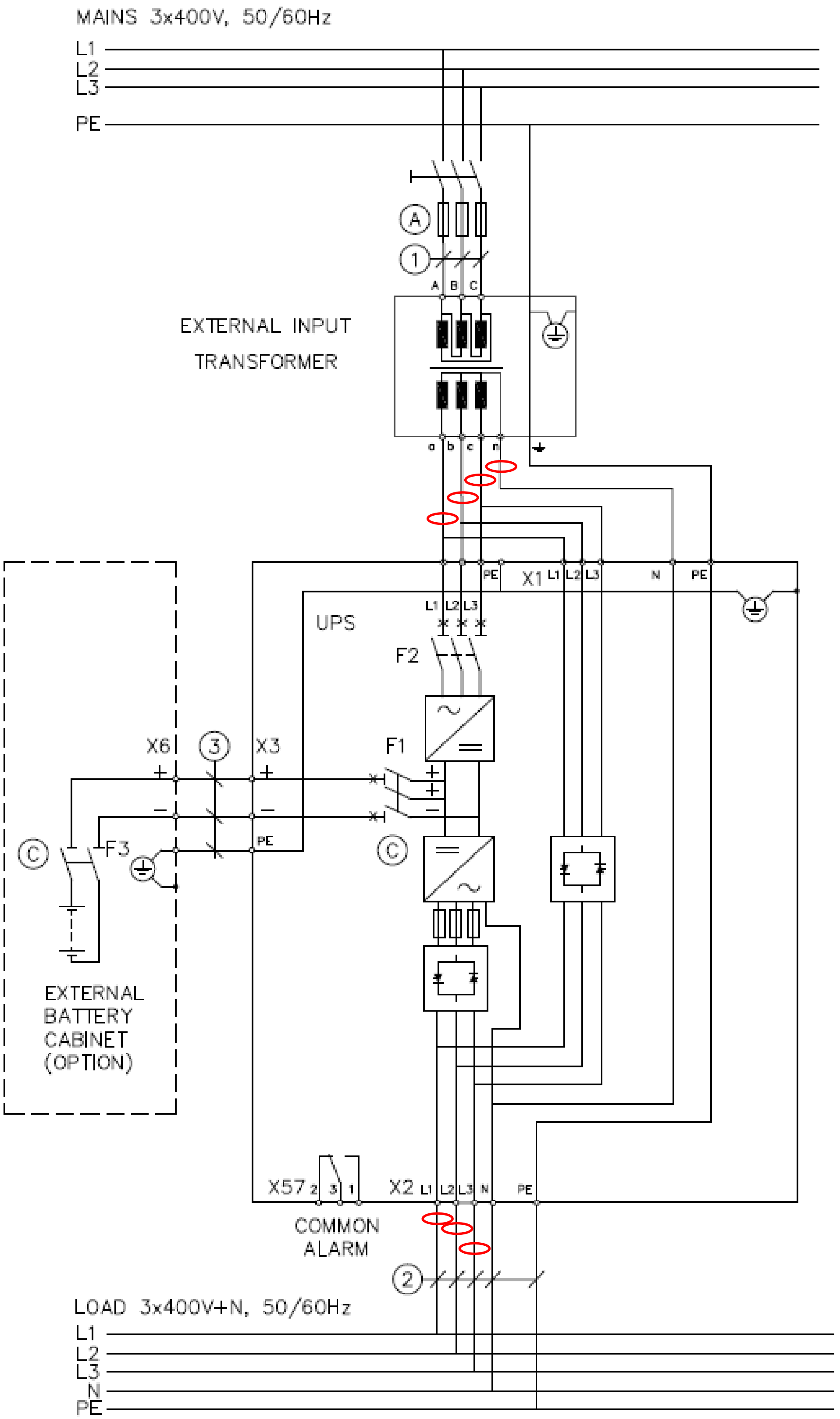
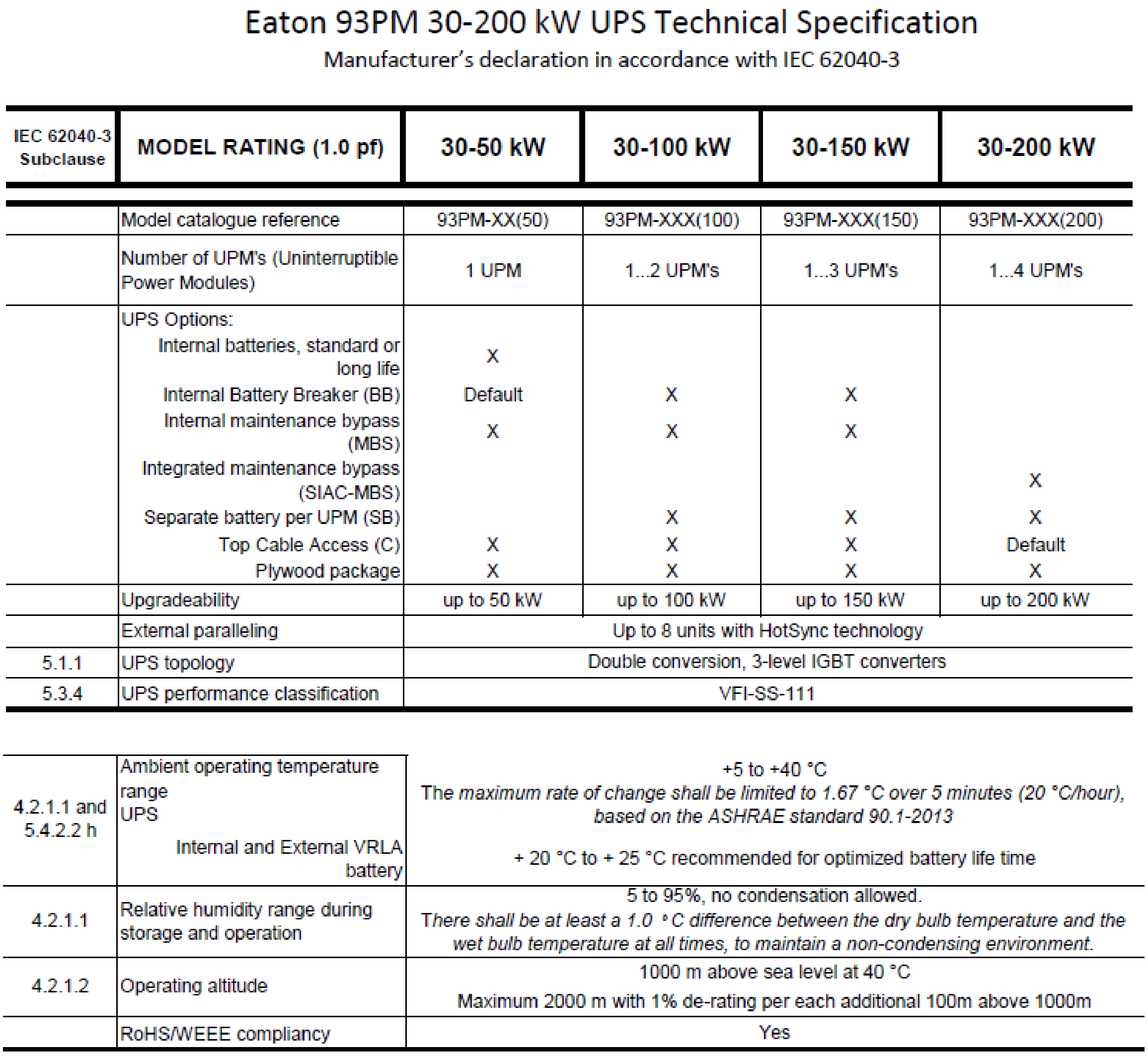
APPENDIX 1. A schematic diagram showing the measurement points.



APPENDIX 2. Captures from the 93PM 30-200 kW Technical Specification [22].



Eaton 93PM 30-200 kW UPS Technical Specification

Manufacturer's declaration in accordance with IEC 62040-3

IEC 62040-3 Subclause	MODEL RATING (1.0 pf)	30-50 kW	30-100 kW	30-150 kW	30-200 kW
	Model catalogue reference	93PM-XX(50)	93PM-XXX(100)	93PM-XXX(150)	93PM-XXX(200)
	Number of UPM's (Uninterruptible Power Modules)	1 UPM	1...2 UPM's	1...3 UPM's	1...4 UPM's
	UPS Options:				
	Internal batteries, standard or long life	X			
	Internal Battery Breaker (BB)	Default	X	X	
	Internal maintenance bypass (MBS)	X	X	X	
	Integrated maintenance bypass (SIAC-MBS)				X
	Separate battery per UPM (SB)		X	X	X
	Top Cable Access (C)	X	X	X	Default
	Plywood package	X	X	X	X
	Upgradeability	up to 50 kW	up to 100 kW	up to 150 kW	up to 200 kW
	External paralleling	Up to 8 units with HotSync technology			
5.1.1	UPS topology	Double conversion, 3-level IGBT converters			
5.3.4	UPS performance classification	VFI-SS-111			

4.2.1.1 and 5.4.2.2 h	Ambient operating temperature range UPS Internal and External VRLA battery	+5 to +40 °C *The maximum rate of change shall be limited to 1.67 °C over 5 minutes (20 °C/hour), based on the ASHRAE standard 90.1-2013* + 20 °C to + 25 °C recommended for optimized battery life time
4.2.1.1	Relative humidity range during storage and operation	5 to 95%, no condensation allowed. *There shall be at least a 1.0 °C difference between the dry bulb temperature and the wet bulb temperature at all times, to maintain a non-condensing environment.*
4.2.1.2	Operating altitude	1000 m above sea level at 40 °C Maximum 2000 m with 1% de-rating per each additional 100m above 1000m
	RoHS/WEEE compliancy	Yes

EFFICIENCY

5.3.2 r and 6.4.1.6	Efficiency in double-conversion, rated linear load	30	40	50	60	80	100	90	120	150	120	160	200kW
	100% load	96,6	96,5	96,3%	96,7	96,6	96,4%	96,7	96,7	96,5%	96,7	96,6	96,4%
	75% load	96,6	96,6	96,6%	96,6	96,7	96,6%	96,7	96,7	96,7%	96,6	96,7	96,6%
	50% load	96,1	96,5	96,6%	96,2	96,6	96,7%	96,4	96,7	96,7%	96,3	96,6	96,7%
	25% load	94,0	95,1	95,7%	93,4	95,5	96,0%	94,0	95,7	96,1%	93,4	95,3	95,9%

	Heat dissipation in double conversion, [W]	30	40	50	60	80	100	90	120	150	120	160	200kW
	100% load	1055	1450	1921 W	2049	2816	3734 W	3071	4095	5440 W	4095	5631	7469 W
	75% load	791	1056	1320 W	1584	2048	2640 W	2304	3071	3839 W	3167	4095	5280 W
	50% load	609	725	880 W	1185	1408	1706 W	1680	2048	2559 W	2305	2816	3413 W
	25% load	479	515	562 W	1060	942	1042 W	1436	1348	1623 W	2120	1973	2138 W
	No load	366 W			760 W			1120 W			1520 W		

	Efficiency in ESS, rated linear load	30	40	50	60	80	100	90	120	150	120	160	200kW
	100% load	99,0	99,1	99,2%	99,1	99,2	99,3%	99,2	99,2	99,3%	99,1	99,2	99,2%
	75% load	99,0	99,0	99,1%	99,0	99,1	99,2%	99,0	99,2	99,2%	99,0	99,1	99,2%
	50% load	98,5	98,9	99,0%	98,7	99,0	99,0%	98,8	99,0	99,2%	98,8	99,0	99,0%
	25% load	97,5	98,1	98,3%	98,4	98,6	98,6%	98,2	98,4	98,7%	98,2	98,4	98,6%

	Heat dissipation in ESS	30	40	50	60	80	100	90	120	150	120	160	200kW
	100% load	303	363	403 W	544	645	705 W	723	968	1057 W	1090	1290	1613 W
	No load	128 W			216 W			340 W			500 W		
	Efficiency in stored energy mode, up to	95,5 %											

ELECTRICAL CHARACTERISTICS

INPUT

5.2.1.a and 5.2.1 b	Rated input voltage	220/380 V; 230/400 V; 240/415 V
	Voltage tolerance Rectifier input	rated voltage -20% / +20%
	Bypass input	rated voltage -10% / +10%
5.2.1 c and 5.2.1 d	Rated input frequency	50 or 60 Hz
	Frequency tolerance	42 to 72 Hz

IEC 62040-3 Subclause	MODEL RATING (1.0 pf)	30-50 kW			30-100 kW			30-150 kW			30-200 kW		
5.2.2 a and 5.2.2 b	Number of input phases	3 phases + neutral + PE											
5.2.2 d	Input power factor	0,99 at 100% load											
		30	40	50	60	80	100	90	120	150	120	160	200kVA
5.2.2 c	Rated rectifier input current, 100% load without charging	45 A	60 A	75 A	90 A	120 A	150 A	135 A	180 A	226 A	180 A	241 A	301 A
5.2.2 f	Maximum rectifier input current	57 A	76 A	95 A	114 A	152 A	190 A	171 A	228 A	285 A	228 A	304 A	380 A
	Rated Bypass input current	44 A	58 A	73 A	87 A	117 A	146 A	131 A	175 A	219 A	175 A	233 A	292 A
5.2.2 h and 5.2.2. i	Input current distortion at rated input current	30	40	50	60	80	100	90	120	150	120	160	200kVA
	Resistive load	< 5%	<3%		<5%	<3%		<5%	<3%		<5%	<3%	
5.2.2 e	In-rush current	≤ 145 A			≤ 150 A			≤ 180 A			≤ 380 A		
5.2.2 k	AC power distribution system compatibility	TN, TT, IT (4-wire)											
	Rectifier ramp-up, at rectifier start and load step	10 A/s (default), configurable. Minimum 1 A/s.											
	Backfeed protection	Yes, for rectifier and bypass lines											

ELECTRICAL CHARACTERISTICS

OUTPUT

5.3.2 k	Output power rating	30kVA; 40kVA; 50kVA; 60kVA; 80kVA; 100kVA; 90kVA; 120kVA; 150kVA; 160kVA; 200kVA	
	Output power factor	1.0	
5.3.2 o and 5.3.2 p	Load power factor, permitted range	From 0,8 lagging to 0,8 leading without de-rating	
5.3.2 f and 5.3.2 g	Number of output phases	3 phase + neutral + PE	
	Crest factor	2,3	
5.3.2 b	Rated output voltage	220/380 V; 230/400 V; 240/415 V, configurable	
	Output voltage variation, steady state	< 1%	
5.3.2 i	Total voltage harmonic distortion 100% linear load 100% non-linear load	< 1,0% < 3,0%	< 1,2% < 3,0%
5.3.2 q	Voltage unbalance at reference unbalanced load	< 0,1%	< 0,6 %
	Phase displacement at reference unbalanced load	< 0,3 deg	< 1,0 deg
5.3.2 j	Voltage transient (r.m.s) and recovery time	0% during transfer from stored energy to normal mode	
		±4% with 110 ms recovery from 100% load step	±4% with 140 ms recovery from 100% load step
5.3.2 c	Rated output frequency	50 or 60 Hz, configurable	
	Output frequency variation	± 0,1 Hz	
5.3.2 d and 5.3.2 e	Maximum frequency range for synchronization with bypass	± 4 Hz as default. User settable ± 0,5 to ± 5 Hz.	
	Maximum synchronized phase error	< 1° with static balanced load	
	Maximum slew-rate when synchronizing	0,4 Hz/s	

IEC 62040-3 Subclause	MODEL RATING (1.0 pf)	30-50 kW	30-100 kW	30-150 kW	30-200 kW
5.3.2 l	Overload capability On inverter	**30, 40, 60, 80, 90, 120, 160 kW** 10 min 135% load 60 sec 155% load 10 sec 185% load 300 ms >185% load		**50, 100, 150, 200 kW** 10 min 110% load 60 sec 125% load 10 sec 150% load 300 ms >150% load	
	Overload capability On inverter, stored energy mode	**30, 40, 60, 80, 90, 120, 160 kW** 10 min 135% load 60 sec 155% load 300 ms >155% load		**50, 100, 150, 200 kW** 10 min 110% load 60 sec 125% load 300 ms >125% load	
	Overload capability On bypass	Continuous < 125% load 10 ms 1000% load			
5.3.2 m	Output current limitation, short-circuit capability	170 A, 400 ms	345 A, 400 ms	510 A, 400 ms	670 A, 400 ms
6.4.2.10.3 and 6.4.2.10.4	Fault clearing capability	35 A gL/gG fuse / B25/C10 circuit breaker	35 A gL/gG fuse / B50/C25 circuit breaker	63 A gL/gG fuse / B63/C32 circuit breaker	63 A gL/gG fuse / B100/C50 circuit breaker

ESS MODE CHARACTERISTICS

	Transfer time to double-conversion	
	Mains available	No break
	Mains failure	< 2 ms in normal transfer conditions, < 10 ms maximum
	Output voltage variation setting	±10% of nominal voltage, default
	Output frequency variation setting	±4 Hz, default
	Storm detection	UPS locks into double-conversion mode when three power line disturbances have forced the unit to double-conversion three times (user adjustable) within a one-hour period (user adjustable).
	High Alert mode	UPS will stay on double-conversion for one hour (user adjustable), after which the unit will automatically return to operate on ESS.

VMMS MODE CHARACTERISTICS

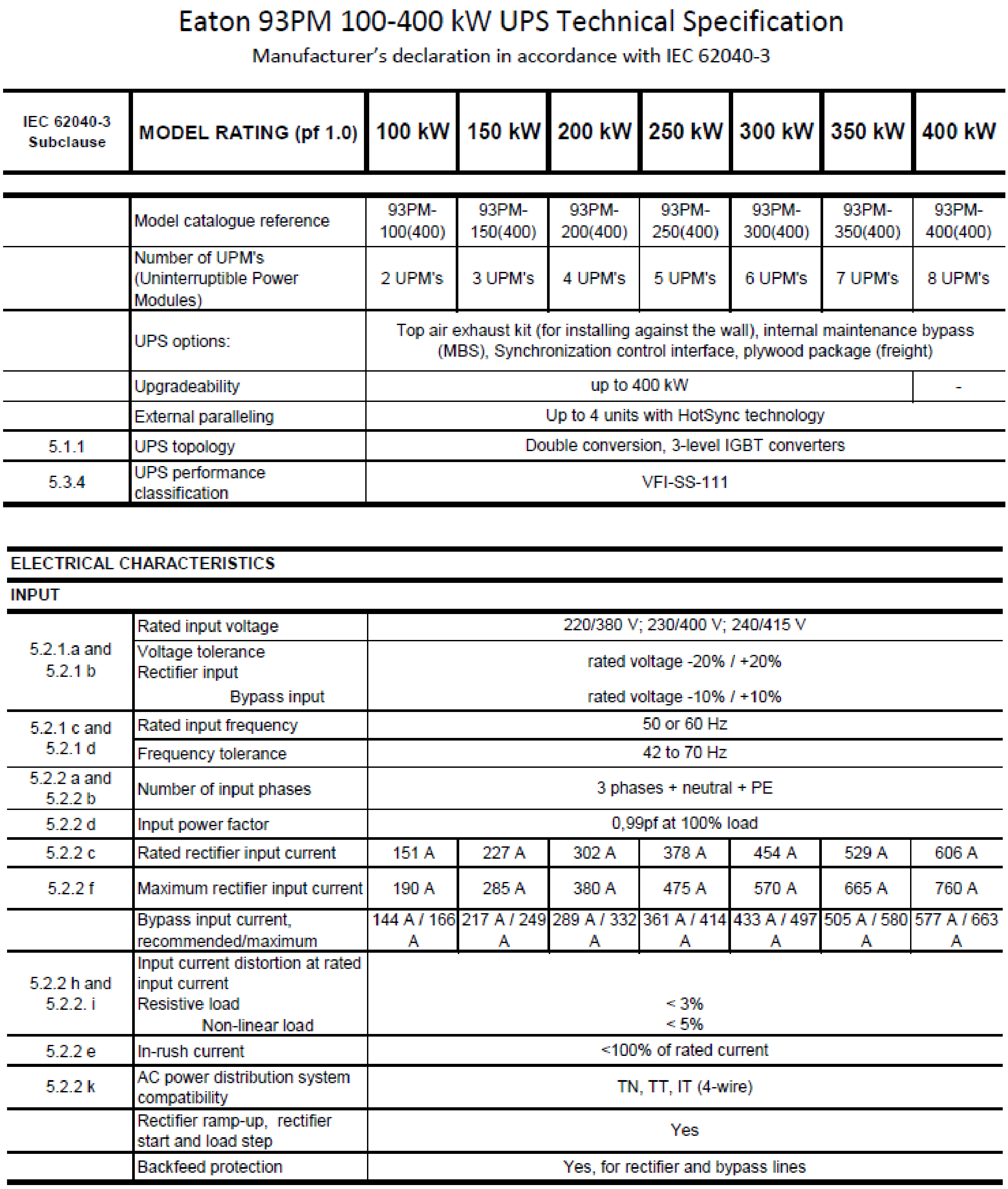
	VMMS Availability	Available for multi-module 93PM UPS system, both between internal modules and modules in an external parallel connected system.
	VMMS operation	When load level per module is less than 55%, VMMS will automatically optimise the number of online modules for optimised operating efficiency. The extra UPMs will be set to ready state mode, capable to transfer online in < 2ms transfer time. The load will be fed in double conversion mode the entire time, even during and after a load step.
	Redundancy level setting	Number of redundant online UPMs (system wide), configurable.
	UPM module rotation	System will automatically rotate the ready state UPMs. Enabled by default, configurable.

BYPASS

	Type of bypass	Static			
	Static Bypass rating	50 kVA	100 kVA	150 kVA	200 kVA
	Static Bypass voltage range	220/380 V; 230/400 V; 240/415 V tolerance -10% / +10% of rated voltage			

IEC 62040-3 Subclause	**MODEL RATING (1.0 pf)**	**30-50 kW**	**30-100 kW**	**30-150 kW**	**30-200 kW**
	Transfer time break	No break			
	Maintenance bypass	Option, internal or external			Option, integrated sidecar or external
	Backfeed protection	Integrated as standard			
	Rated conditional short-circuit current, Icc Static bypass	100 kA (internal ultra rapid fusing)			
	Optional internal or integrated Maintenance bypass	10 kA*	25 kA*	10 kA*	50 kA*
		*using external protective fuse			
	Internal static bypass ultra-rapid fuse	Bussmann 160LET	Bussmann 550 A 170M4465	Bussmann 900 A 170M4419	
	Bypass fuse i^2t value Pre-arc i^2t Total clearing i^2t	 1 100 A^2s 16 000 A^2s	 96 100 A^2s 230 000 A^2s	 155 000 A^2s 850 000 A^2s	
	External bypass protective fuse, recommended rating 3x	30 40 50 63 A 80 A 100 A	60 80 100 125 A 160 A 200 A	90 120 150 200 A 250 A 315 A	120 160 200kVA 250 A 315 A 400 A

APPENDIX 3. Captures from the 93PM 100-400 kW Technical Specification [23].



Eaton 93PM 100-400 kW UPS Technical Specification

Manufacturer's declaration in accordance with IEC 62040-3

IEC 62040-3 Subclause	MODEL RATING (pf 1.0)	100 kW	150 kW	200 kW	250 kW	300 kW	350 kW	400 kW
	Model catalogue reference	93PM-100(400)	93PM-150(400)	93PM-200(400)	93PM-250(400)	93PM-300(400)	93PM-350(400)	93PM-400(400)
	Number of UPM's (Uninterruptible Power Modules)	2 UPM's	3 UPM's	4 UPM's	5 UPM's	6 UPM's	7 UPM's	8 UPM's
	UPS options:	Top air exhaust kit (for installing against the wall), internal maintenance bypass (MBS), Synchronization control interface, plywood package (freight)						
	Upgradeability	up to 400 kW						-
	External paralleling	Up to 4 units with HotSync technology						
5.1.1	UPS topology	Double conversion, 3-level IGBT converters						
5.3.4	UPS performance classification	VFI-SS-111						

ELECTRICAL CHARACTERISTICS								
INPUT								
5.2.1.a and 5.2.1 b	Rated input voltage	220/380 V; 230/400 V; 240/415 V						
	Voltage tolerance Rectifier input Bypass input	rated voltage -20% / +20% rated voltage -10% / +10%						
5.2.1 c and 5.2.1 d	Rated input frequency	50 or 60 Hz						
	Frequency tolerance	42 to 70 Hz						
5.2.2 a and 5.2.2 b	Number of input phases	3 phases + neutral + PE						
5.2.2 d	Input power factor	0,99pf at 100% load						
5.2.2 c	Rated rectifier input current	151 A	227 A	302 A	378 A	454 A	529 A	606 A
5.2.2 f	Maximum rectifier input current	190 A	285 A	380 A	475 A	570 A	665 A	760 A
	Bypass input current, recommended/maximum	144 A / 166 A	217 A / 249 A	289 A / 332 A	361 A / 414 A	433 A / 497 A	505 A / 580 A	577 A / 663 A
5.2.2 h and 5.2.2. i	Input current distortion at rated input current Resistive load Non-linear load	< 3% < 5%						
5.2.2 e	In-rush current	<100% of rated current						
5.2.2 k	AC power distribution system compatibility	TN, TT, IT (4-wire)						
	Rectifier ramp-up, rectifier start and load step	Yes						
	Backfeed protection	Yes, for rectifier and bypass lines						

APPENDIX 4. Measurements template.

Test instruments

Equipment	Make and model	Accuracy
Digital power analyzer	Yokogawa WT1800	±(0.1% of reading + 0.2% of range) Errors regarding PF included for the inductive/capacitive measurements. 1.5 multiplier to the reading errors for accuracy at 1 year compared to 6 months. Active power range of 4.5 kW for 3P4W wiring unit utilized. The voltage range of 300 V and the current range of 5 A. [24].
Current transformers	Eaton HF4B 300:5	0.2S. [25]

Tables of measurements

		Resistive load											
		100 % load			75 % load			50 % load			25 % load		
		50 kW			37,5 kW			25 kW			12,5 kW		
Normal mode		1	2	3	1	2	3	1	2	3	1	2	3
P_{input}	L_1	17348	17347	17360	12943	12966	12945	8701	8705	8691	4303	4305	4300
	L_2	17342	17365	17358	13031	13011	13016	8744	8736	8741	4308	4311	4310
	L_3	17426	17423	17424	13157	13159	13128	8850	8845	8849	4387	4385	4384
	Total	52116	52135	52142	39130	39136	39089	26296	26286	26281	12998	13001	12994
Qinput	L_1	-1115	-1102	-1126	-1208	-1213	-1233	-1334	-1348	-1372	-1559	-1568	-1579
	L_2	-1063	-1073	-1084	-1231	-1216	-1221	-1384	-1376	-1404	-1600	-1604	-1616
	L_3	-1283	-1276	-1282	-1402	-1382	-1423	-1493	-1498	-1524	-1643	-1657	-1659
	Total	-3460	-3450	-3492	-3841	-3811	-3877	-4211	-4222	-4301	-4802	-4829	-4855
S_{input}	L_1	17384	17382	17396	12999	13022	13003	8803	8808	8799	4577	4581	4581
	L_2	17375	17399	17392	13089	13068	13073	8853	8844	8853	4595	4600	4603
	L_3	17473	17470	17471	13231	13232	13205	8975	8971	8979	4685	4688	4688
	Total	52232	52250	52260	39319	39321	39281	26632	26623	26631	13857	13869	13871
pf_{input}		0.9978	0.9978	0.9978	0.9952	0.9953	0.9951	0.9874	0.9873	0.9869	0.938	0.9374	0.9367
P_{output}	L_1	16791	16803	16793	12669	12668	12670	8489	8481	8484	4216	4217	4215
	L_2	16692	16690	16698	12596	12602	12598	8530	8528	8524	4132	4132	4133
	L_3	16600	16606	16603	12466	12464	12461	8375	8377	8378	4137	4138	4138
	Total	50083	50099	50093	37731	37734	37730	25394	25386	25386	12485	12486	12485
pf_{output}		1	1	1	1	1	1	1	1	1	1	1	1
Efficiency		96.099	96.094	96.071	96.424	96.419	96.524	96.569	96.576	96.595	96.054	96.037	96.087

Average efficiency (%)	96.1			96.5			96.6			96.1		

Standard deviation total input power (1.-3.)	13.4536			25.5799			7.6376			3.5119		
Standard deviation total output powers (1.-3.)	8.0829			2.0817			4.6188			0.5774		
Uncertainties of meas. Devices (1. CT; 2. WT1800: reading; range) ± (%)	0.002	0.002	2.25	0.002	0.002	2.25	0.002	0.002	2.25	0.002	0.002	2.25
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Input power average	60.2		46.4	45.2		35.2	30.4		24.1	15.0		12.6
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Output power average	57.8		44.7	43.6		34.0	29.3		23.3	14.4		12.1
Standard uncertainty of measurements (1. Total input powers 2. Total output powers) ± (W)	7.8		4.67	14.8		1.20	4.4		2.67	2.0		0.33
Combined standard uncertainty (1. Input power; 2. Output power) ± (W)	76.4		73.2	59.1		55.3	39.0		37.53	19.7		18.8
Expanded uncertainties for input and output powers with K = 2 (95 % coverage) ± (W)	152.9		146.5	118.3		110.5	78.0		75.07	39.3		37.7
Combined uncertainty ± (%)	1.13			1.15			1.14			1.16		

		Resistive load								
		75 % load			50 % load			25 % load		
		37,5 kW			25 kW			12,5 kW		
Capacitive RP		1	2	3	1	2	3	1	2	3
P_{input}	L_1	12958	12969	12967	8668	8665	8666	4313	4319	4318
	L_2	13087	13089	13088	8868	8867	8873	4533	4524	4526
	L_3	13114	13116	13123	8903	8909	8896	4535	4542	4532
	Total	39159	39174	39179	26440	26441	26435	13381	13385	13376
Qinput	L_1	-11435	-11476	-11491	-14783	-14942	-14967	-16711	-16673	-16678
	L_2	-11371	-11407	-11410	-14741	-14889	-14946	-16735	-16702	-16719
	L_3	-11508	-11538	-11541	-14876	-15004	-15066	-16850	-16813	-16801
	Total	-34313	-34421	-34442	-44400	-44834	-44979	-50296	-50188	-50199
S_{input}	L_1	17282	17318	17326	17137	17272	17295	17258	17223	17228
	L_2	17337	17362	17364	17203	17329	17381	17338	17304	17321
	L_3	17447	17469	17476	17337	17449	17496	17450	17416	17402
	Total	52066	52149	52166	51677	52051	52173	52046	51943	51951
pf_{input}		0.7521	0.7512	0.751	0.5116	0.508	0.5067	0.2571	0.2577	0.2575
P_{output}	L_1	12677	12683	12680	8490	8489	8487	4218	4217	4217
	L_2	12599	12604	12601	8534	8532	8535	4134	4134	4136
	L_3	12473	12470	12466	8372	8375	8371	4134	4136	4134
	Total	37749	37757	37747	25395	25395	25393	12486	12486	12487
pf_{output}		1	1	1	1	1	1	1	1	1
Efficiency		96.344	96.381	96.401	96.058	96.045	96.048	93.353	93.285	93.31

Average efficiency (%)	96.4	96.1	93.3

Standard deviation total input power (1.-3.)	10.4083			3.2146			4.5092		
Standard deviation total output powers (1.-3.)	5.2915			1.1547			0.5774		
Uncertainties of meas. Devices (1. CT; 2. WT1800: reading; range) ± (%)	0.002	0.002	2.25	0.002	0.002	2.25	0.002	0.002	2.25
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Input power average	45.2		54.8	30.5		49.4	15.5		40.9
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Output power average	43.6		34.0	29.3		23.3	14.4		12.1
Standard uncertainty of measurements (1. Total input powers 2. Total output powers) ± (W)	6.0		3.06	1.9		0.67	2.6		0.33
Combined standard uncertainty (1. Input power; 2. Output power) ± (W)	71.3		55.4	58.1		37.5	43.8		18.8
Expanded uncertainties for input and output powers with K = 2 (95 % coverage) ± (W)	142.6		110.7	116.2		74.9	87.6		37.7
Combined uncertainty ± (%)	1.27			1.41			1.79		

		Resistive load								
		75 % load			50 % load			25 % load		
		37,5 kW			25 kW			12,5 kW		
Inductive RP		1	2	3	1	2	3	1	2	3
P_{input}	L_1	13291	13276	13283	9112	9162	9142	4732	4738	4755
	L_2	13205	13208	13213	9063	9044	9053	4661	4667	4668
	L_3	13287	13282	13289	9157	9133	9138	4781	4762	4747
	Total	39783	39766	39785	27333	27339	27334	14174	14167	14170
Qinput	L_1	11344	11054	11224	14619	14651	14624	14306	14251	14289
	L_2	11281	11004	11171	14518	14523	14507	14223	14174	14207
	L_3	11272	10969	11132	14570	14585	14576	14332	14272	14296
	Total	33897	33027	33527	43708	43759	43708	42860	42697	42791
S_{input}	L_1	17474	17275	17390	17227	17280	17247	15068	15018	15059
	L_2	17368	17191	17302	17115	17109	17100	14967	14922	14954
	L_3	17424	17226	17336	17208	17208	17204	15108	15046	15063
	Total	52266	51692	52028	51550	51597	51551	45143	44986	45076
pf_{input}		0.7612	0.7693	0.7647	0.5302	0.5299	0.5302	0.314	0.3149	0.3144
P_{output}	L_1	12661	12658	12656	8480	8480	8479	4215	4213	4212
	L_2	12602	12607	12609	8532	8529	8533	4131	4131	4134
	L_3	12461	12462	12468	8382	8382	8379	4139	4141	4139
	Total	37725	37726	37733	25393	25390	25390	12484	12485	12486
pf_{output}		1	1	1	1	1	1	1	1	1

Average efficiency (%)	94.8	92.9	88.1

Standard deviation total input power (1.-3.)	10.4403			3.2146			3.5119		
Standard deviation total output powers (1.-3.)	4.3589			1.7321			1.0000		
Uncertainties of meas. Devices (1. CT; 2. WT1800: reading; range) ± (%)	0.002	0.002	2.25	0.002	0.002	2.25	0.002	0.002	2.25
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Input power average	45.9		54.7727	31.6		49.6063	16.4		37.3796
Standard uncertainty of meas. Devices (1. CT; 2. WT1800; reading + range) ± (W) of Output power average	43.6		33.9724	29.3		23.2883	14.4		12.1114
Standard uncertainty of measurements (1. Total input powers 2. Total output powers) ± (W)	6.0		2.52	1.9		1.00	2.0		0.58
Combined standard uncertainty (1. Input power; 2. Output power) ± (W)	71.7		55.3	58.8		37.5	40.9		18.8
Expanded uncertainties for input and output powers with K = 2 (95 % coverage) ± (W)	143.5		110.6	117.7		74.9	81.7		37.7
Combined uncertainty ± (%)	1.24			1.35			1.55		