

TRNSYS

a TRaNsient SYstem Simulation program

GREEN DATA CENTRE LIBRARY

Volume 1

Mathematical Reference



About This Manual

The information presented in this manual is intended to provide a detailed mathematical reference for the Green Data Centre Library in TRNSYS 17. This manual is not intended to provide detailed reference information about the TRNSYS simulation software and its utility programs. More details can be found in other parts of the TRNSYS documentation set.

Revision history

- 2015-06 For version 01

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1. INTRODUCTION

This manual provides a detailed reference on each component model (Type) in TRNSYS. This manual provides the mathematical basis of the model, as well as other elements that the user should consider whenever using the model (e.g. data file format, etc.). This guide is organized in components categories that match the upper level directories in the Simulation Studio proformas. These categories are:

- IT Equipment
- Electrical Components
- Electrical Generation

For the IT Equipment, the following types are developed:

- 4000 IT Loads

The electrical components types are developed in two different levels. These types are used in order to calculate electrical losses in the process.

Electrical Components where performance is based on quadratic dependence on load factor

These types use experimental coefficients which can be changed by the user. Default values are mainly extracted from Schneider Electric TradeOff Tools™ for Data Centre design.

Electrical Components whose performances are based on manufacturers properties

. The purpose of these types is to enable the setting of loss coefficients directly from the specific manufacturer database.

As a consequence, the user is able to choose the option that fits better its purpose. In the following chapters, electrical components types will be grouped for families but peculiarities will be specified for each type:

- Uninterruptible Power Supply Unit (UPS)
 - Losses UPS
 - Type 4001 based on load factor dependence
 - Type 4011 based on manufacturer properties
 - Detailed UPS
 - Type 4015
- Power Distribution Unit (PDU)
 - Type 4002 based on load factor dependence
- Wire
 - Type 4003 based on load factor dependence
 - Type 4010 based on manufacturer properties
- Switchgear unit (SWG)
 - Type 4004 based on load factor dependence
 - Type 4009 based on manufacturer properties
- Standby losses of a Generator (GE)
 - Type 4005 based on reference power
- Lighting consumption (LGT)
 - Type 4006 based on reference power
 - Type 4013 based on area
- Miscellaneous consumption (MISC)
 - Type 4007 based on reference power
- Transformer (TR)
 - Type 4008 based on manufacturer properties
- Power Supply Unit (PSU)
 - Type 4012 based on manufacturer properties

For the Electrical Generation, a type for Wave Energy Converter (WEC) has been developed:

- 4014 Wave Energy Converter

2. IT POWER

2.1 TYPE 4000. IT LOADS

IT load is a model for the IT equipment, mainly servers, storage and network. IT transforms an IT load curve into a power consumption curve by considering the effects of non-linear power-consumption , increasing power consumption at higher temperatures and Green Algorithms.

NOMENCLATURE

| | | |
|-----------------------|--------|-----------------------------------------|
| $IT_{Immovable}$ | [%] | IT load that can not be shifted in time |
| $IT_{Movable}$ | [%] | IT load that can be shifted in time |
| T_{in} | [°C] | Inlet temperature for the servers |
| $RER_{current}$ | [%] | Current renewable Energy Ratio |
| S_{uear} | [year] | Year of server manufacturer |
| $S_{allocation}$ | [%] | Server allocation method |
| P_{IT} | [kW] | IT Power Capacity |
| $IT_{PeakLoadFactor}$ | [%] | Expected IT Power peak |
| $S_{consolidation}$ | [0,1] | Consolidation |
| S_{green} | [0,1] | Green Algorithm for load shifting |
| $S_{liquidcooling}$ | [0,1] | Liquid cooling vs air cooling |
| $RER_{threshold}$ | [%] | Threshold RER % |
| $IT_{backlog}$ | [h] | Maximum IT backlog |
| $C_{storage}$ | [%] | Storage components |
| $C_{Network}$ | [%] | Network components |
| S_{idle} | [%] | Server power consumption when idle |

MATHEMATICAL DESCRIPTION

The basic idea is:

$$P_{el} = \text{Current IT Load [\%]} * \text{IT Power [kW]} \quad (1)$$

Both the IT load and the IT power can be modified by the parameters and the inputs. Additionally, this type enables to store some of the IT load from the input “IMovable” in the IT backlog and withdraw it again. The IT backlog is simply modelled as storage tank.

The steps of the calculation are as follows:

Nominal IT Power

Calculate the nominal IT power for the internal calculations, which is smaller than the IT power capacity PIT:

$$P_{IT,Nominal} = P_{IT} * IT_{PeakLoadFactor} * IT_{Occupancy} \quad (2)$$

Apply the Green Algorithms:

If there is space in the IT backlog (ITBacklog, Current < ITBacklog) and the renewable energy fraction is below the threshold (RERcurrent < RERThreshold) then store IT load in the backlog proportional to RERcurrent:

$$IT_{AmountToStore} = I_{movable} \left(1 - \frac{RER_{current}}{RER_{Threshold}}\right) \quad (3)$$

If the IT Backlog contains sufficient data (ITBacklog, Current > 0) and the renewable energy fraction is above the threshold (RERcurrent > RERThreshold) then withdraw a proportional amount from the IT backlog.

$$IT_{AmountToWithdraw} = \frac{(RER_{current} - RER_{Threshold})}{(1 - RER_{Threshold})} * (1 - I_{movable} - I_{nonmovable}) \quad (4)$$

Network Components, Storage Components

It is assumed that the electric power consumption of the network components and the storage components is constant. Network Components in this context are switches, core switches, routers, firewalls and so on. Storage components are the tape libraries and storage appliances, such as EMC Netapp. For instance, let us consider a Data Centre with a nominal IT power of 100 kW and 10% storage components, 10% network components implies that 80% is influenced by the movable IT load and immovable IT Load. Moreover, 20% is a permanent base load. The calculation of the server power consumption is shown below:

$$P_{Servers} = P_{IT,Nominal} * (1 - C_{Storage} - C_{Network}) \quad (5)$$

$$P_{Network} = P_{IT,Nominal} * C_{Network} \quad (6)$$

$$P_{Storage} = P_{IT,Nominal} * C_{Storage} \quad (7)$$

Calculate the IT load percentage

$$I_{Load,Green} = I_{nonmovable} + I_{movable} + I_{AmountToWithdraw} - I_{AmountToStore} \quad (8)$$

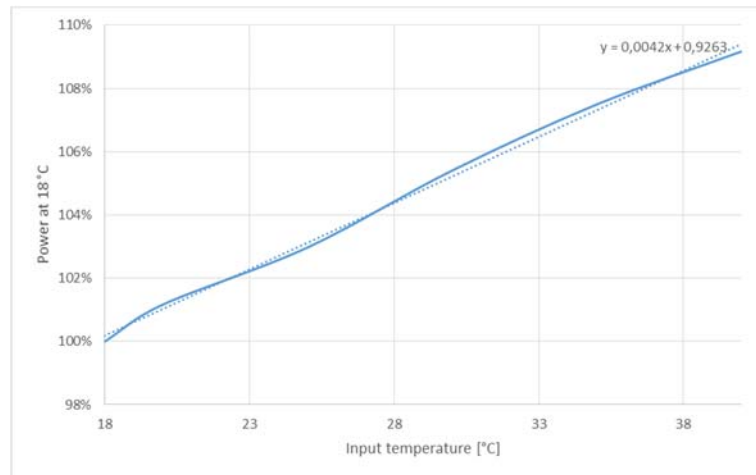
Apply the temperature power equation

The influence of temperature on the power consumption varies Depending on the cooling technology (air cooling or liquid cooling)

For liquid cooling this equation is:

$$P_{IT,Temperature} = P_{IT,Nominal} * (0.00418988 * T_{in} + 0.92633691) \quad (9)$$

As a first approximation the measurements from the TUC test bench will be used, see Figure 1. It is assumed that the IT equipment has a very low heat capacity and that the step size is large enough to completely neglect thermal inertia. Another assumption is that the air/water inlet temperature converts directly into CPU temperature. The power increase can augment the electric load beyond the nominal IT power, since it is assumed that the nominal IT power refers to the maximum power at 18°C. So a 100 kW DC can rise up to 110 kW if it runs at 40°C.

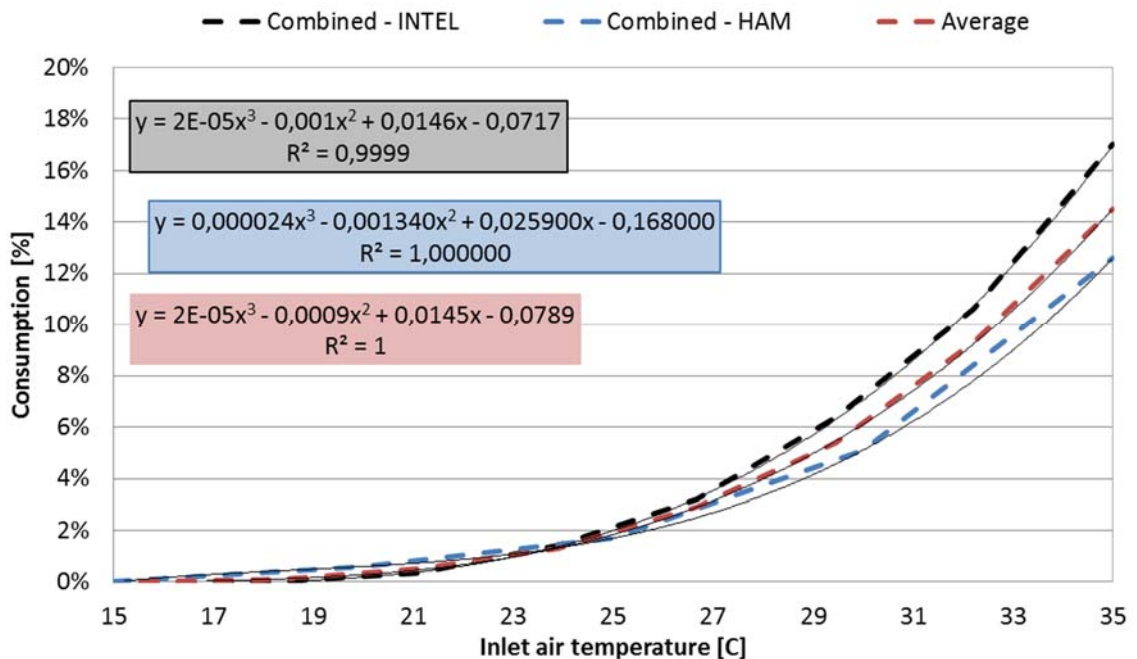


Graphic 1 Electric load increase for increased input temperature

For air cooling, this equation is used:

$$P = P_{IT,Nominal} + P_{IT,Nominal} * (0.000024 * T_{in}^3 - 0.001340 * T_{in}^2 + 0,0259 * T_{in}^2 - 0,168) \tag{10}$$

The equation is based on measurements done by APC (White Paper 138) and Sang-Woo Ham (Optimum supply air temperature ranges of various air-side economizers in a modular data center).



Graphic 2 Consumption versus inlet air temperature

Year of Server Manufacture

The IT load is assumed to be in 2013 Values. Since computers get faster every year, it is possible to calculate the power consumption for an identical IT load using computers from another year. If the year of server manufacture is not “-1”, the following equation is applied to the power consumption:

$$S_{Age} = S_{year} - 2013 \quad (11)$$

$$P_{IT,Age} = \frac{P_{IT,Temperature}}{0.011718 * S_{Age}^2 + 0.217816 * S_{Age} + 1.025515} \quad (12)$$

For a hypothetical data centre with 100 kW, these are the results:

- For 2013 it will have a power of 97 kW
- For 2014 it will have a power of 80 kW
- For 2010 it will have 210 kW.
- For 2004 it would be 6 978 kW

If a server age of -1 is entered, then the 100 kW is unchanged.

Additionally the server age determines the power consumption at partial loads according to the next figure:

$$S_{Idle,Effective} = 0.00461 * S_{Age}^2 - 0.03740 * S_{Age} + 0.21196 \quad (13)$$

This gives about 25% for 2013 and close to 100% for 2004. So, if a year of server manufacture is set, the S_{Idle} is overwritten. If the year of server manufacture is -1, then this assignment is used:

$$S_{Idle,Effective} = S_{Idle} \quad (14)$$

IT Load to power curves

The curves are applied for calculating the power consumption based on the IT load. Measurements by BSC reveals that for different loads (web, hpc, data) the power consumption at for example 50% load can be quite different. The curves used in the type are:

Web:

$$IT_{effective} = IT_{Load,Green} * 49.8 + 37.1 \quad (15)$$

Data:

If the IT Load is between 0% and 23.3%:

$$IT_{effective} = IT_{Load,Green} * 90.9 + 34.92 \quad (16)$$

Else

$$IT_{effective} = IT_{Load,Green} * 90.9 + 34.92 - 361.93 * (IT_{Load,Green} - 0.233) \quad (17)$$

HPC:

If the IT load is between 0% and 5%:

$$IT_{effective} = IT_{Load,Green} * 252.43 + 35.0 \quad (18)$$

Else

$$IT_{effective} = IT_{Load,Green} * 672.23 + 14.01 - 631.93 * (IT_{Load,Green} - 0.05) \quad (19)$$

Allocation / Consolidation

The allocation parameter determines if 50% load means 50% of all servers are running at 100% ($S_{allocation} = 1$) or if 50% means that 100% of all servers are running at 50% ($S_{allocation} = 0$). Consolidation in this context means that $S_{allocation} = 1$ and that idle servers are turned off. Enabling consolidation enables allocation automatically. The power consumption of the servers at idle is calculated from the BSC IT load to power curves by putting in an IT load of 0.

So whether ($S_{allocation} = 0$) or ($S_{allocation} = 1$), the equation used is always:

$$P_{IT,Result} = IT_{effective} * P_{IT,Age} * (1 - S_{Idle,Effective}) + P_{IT,Age} * S_{Idle,Effective} \quad (20)$$

If consolidation is turned on ($S_{\text{consolidation}}=1$) then the equation becomes

$$P_{IT,Result} = IT_{effective} * P_{IT,Age} * (1 - S_{Idle,Effective}) \quad (21)$$

Total Power Consumption

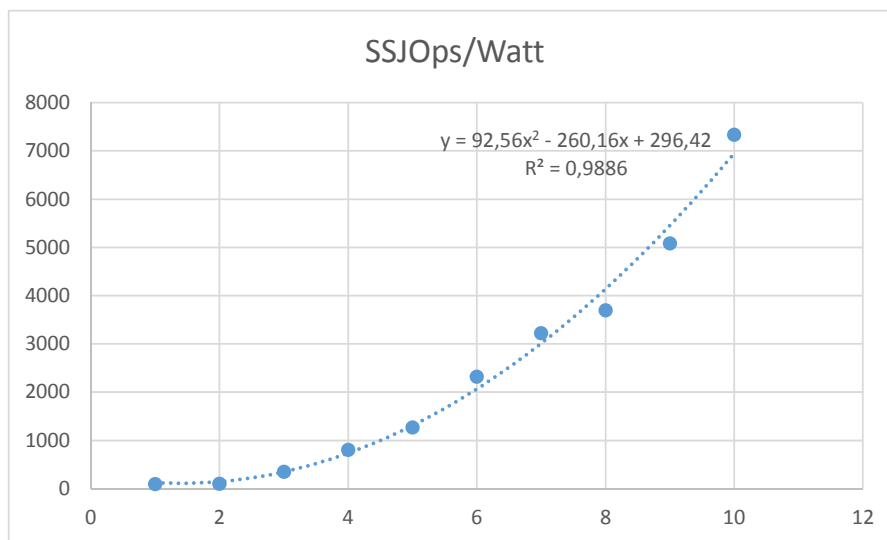
Consequently, the total power consumption is:

$$P_{Total} = P_{IT,Result} + P_{Network} + P_{Storage} \quad (22)$$

ADDITIONAL INFORMATION

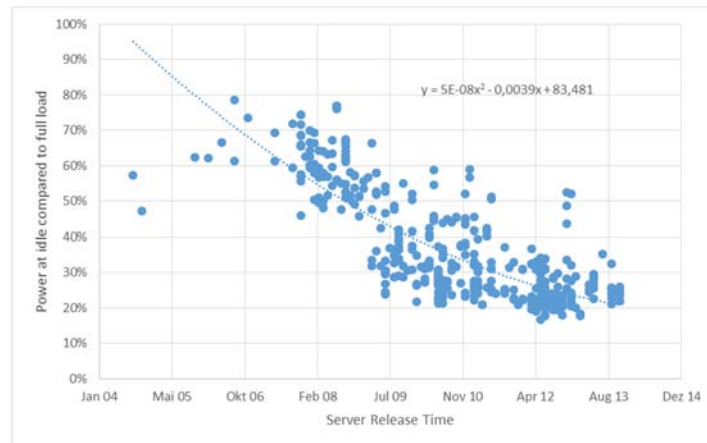
Year of Server Manufacture

As foundation for the year of the server manufacture, the data from SPECpower_ssj2008® has been used. This is displayed in Figure 3..



Graphic 3 Increase in processing power over the years

As reference for the idle power consumption also data from specPower_ssj2008 has been used. This is graphed in Figure 4.



Graphic 4 Power at idle compared to power at full load for different years

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Immovable IT Load (%)

IT load that cannot be shifted in time and has to be executed right away, for example for web workload.

- Movable IT Load (%)

IT load that can be shifted in time, for example HPC workload

- T_{in} (°C)

Inlet temperature for servers

- RER current (%)

Current renewable energy ratio

Outputs are listed below:

- Electric load (kW)
- Real IT Load (%)
- Change in IT backlog (%)
- Electricity used by networking (kW)
- Electricity used by storage (kW)

- Current IT backlog (h)
- Maximum IT power consumption (kW)

Parameters are described below:

- Year of server manufacture (-)
- *Server allocation* (-)
- *Consolidation* (Boolean)
- *Green algorithm* (Boolean)
- Threshold RER (%)
- Maximum IT backlog (h)
- IT Power capacity (kW)
- IT Peak Load Factor (%)
- Network components (%)
- Storage components (%)
- Idle Factor (%)

3. UNINTERRUPTIBLE POWER SUPPLY UNIT (UPS)

3.1 TYPE 4001. UPS LOSSES BASED ON LOAD FACTOR DEPENDENCE

An Uninterruptible Power Supply (from now UPS) is a combination of power converters, switches and energy storage media, e.g. batteries. Such a power supply system guarantees ongoing supply to the load in case of supply voltage failure. At the same time, voltage and frequency are still within the static and dynamic limits defined by the load. The international product standard IEC 62040-3 [1] classifies UPS into classes 1, 2 or 3 depending on the load limits.

Type 4001 is an empirical model for UPS. The model uses a mathematical equation, based on empirical coefficients, in order to describe the operational losses of a UPS. The model does not consider the UPS battery. Therefore, the coefficients include the losses due to the double conversion, AC/DC and DC/AC, realized by the UPS converters. If the efficiency curve is known, then these coefficients are given by , data regression technique described by Avelar, V. et al [2]. As an example, a set of values for the coefficients can be found in the tool provided by Schneider [3].

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| C_F | [-] | No load losses coefficient. |
| C_P | [-] | Proportional losses coefficient. |
| C_Q | [-] | Square – law losses coefficient. |
| C_S | [-] | Sizing coefficient. |
| ζ_{UPS} | [kW] | Power losses of the UPS. |
| Eff_{UPS} | [%] | Efficiency of the UPS. |
| LF | [-] | Load factor of the UPS. |

| | | |
|-----------|------|----------------------------------|
| P_{in} | [kW] | Power from grid side of the UPS. |
| P_N | [kW] | Nominal power of the UPS. |
| P_{out} | [kW] | Power to load side of the UPS. |
| P_{Ref} | [kW] | Reference power. |

MATHEMATICAL DESCRIPTION

The component calculates the electrical losses (ζ_{UPS}), due to the double conversion of currents inside the UPS, based on the nominal power (P_N), the load factor (LF) and the three losses coefficients (C_F , C_P and C_Q).

The type computes the nominal power of the UPS by multiplying the sizing coefficient (C_S) by the reference power of the system (P_{Ref}), equation (1). The load factor is the percentage between the power to the load side of the UPS (P_{out}) and the nominal power of the UPS as shown in equation (2). The efficiency curve given by manufacturers provides the losses coefficients as shown in Avelar, V. et al [2]. These coefficients are:

- No load losses coefficient (C_F): describes the UPS standby losses, losses at 0% load, attributable to powering such things as: transformers, logic boards and communication cards. These losses are independent of the load.
- Proportional losses coefficient (C_P): As more power is added to the UPS, a larger amount of power will be flowing by various components in its power path, thus, losses will increase. This coefficient, describes the losses that grow linearly with the load factor.
- Square-law losses coefficient (C_Q): As more power is added to the UPS, more current flows through its components.. This coefficient, describes the losses that grow quadratically with the load factor.

Therefore, the model considers the five following equations in order to compute the electrical losses of the UPS component.

Nominal power of the UPS:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Load factor of the UPS:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (2)$$

Power losses of the UPS:

$$\zeta_{UPS} = P_N \cdot C_F + P_N \cdot C_P \cdot LF + P_N \cdot C_Q \cdot LF^2 \quad [kW] \quad (3)$$

Power from grid side of the UPS:

$$P_{in} = P_{out} + \zeta_{UPS} \quad [kW] \quad (4)$$

Efficiency of the UPS:

$$Eff_{UPS} = \left(\frac{P_{out}}{P_{in}} \right) * 100 \quad [\%] \quad (5)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for the Data Centre according to [3]. the installed IT power must be taken as the reference power if the UPS is installed into a Data Centre.

Table 1 Coefficients for different types of UPS [3].

| System | C_S | C_F | C_P | C_Q |
|----------------------------|-------|-------|-------|-------|
| Legacy UPS | 1.4 | 0.005 | 0.005 | 0.040 |
| Typical UPS | 1.3 | 0.005 | 0.005 | 0.028 |
| High efficiency UPS | 1.3 | 0.005 | 0.005 | 0.007 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are:

- Power to load side of the UPS (*kW*)

Power send to the load connected at the UPS. This amount of power cannot exceed the nominal power of the component.

On the other hand, outputs are:

- Power losses of the UPS (kW)

Electrical losses generated by the UPS converters
- Power from grid side of the UPS (kW)

Power feed to the UPS in order to satisfy the load demand. This power cannot exceed the nominal power of the component.
- Load factor of the UPS (-)

This value defines the percentage of the total capacity at which the UPS is working. A load factor of 1 means that the component is working at its full capacity. This value cannot be lower than 0 or greater than 1.
- Efficiency of the UPS (%)

Efficiency value of UPS.

Additionally, Parameters are :

- Sizing coefficient (-)

This coefficient is used to approximate the nominal power of the component. The nominal power is calculated multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.
- No load losses coefficient (-)

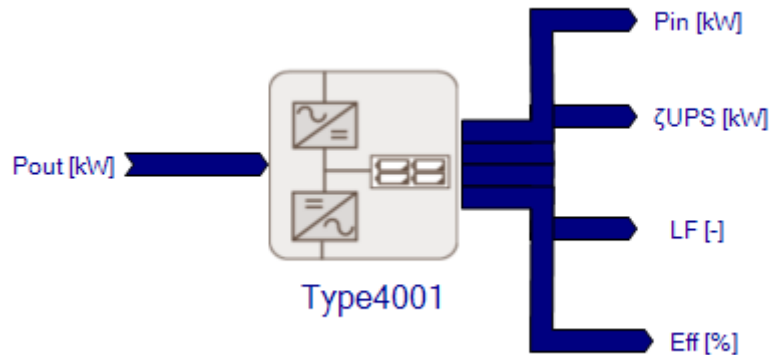
Describes the UPS standby losses.
- Proportional losses coefficient (-)

Describes the UPS losses that grow linearly with the load factor.
- Square-law losses coefficient (-)

Describes the UPS losses that grow in a quadratic way with the load factor.

- Reference power (kW)

The reference power is the installed power of our system. If the UPS is installed into a Data Centre, the installed IT power must be taken as the reference power.



Graphic 5 Scheme of type 4001

REFERENCE

[1] International Standard, IEC 62040-3, Uninterruptible power systems (UPS), PART 3: Method of specifying the performance and test requirements, First edition, 1999-2003.

[2] Avelar, V. Making Large UPS Systems More Efficient, White paper #108, APC, Schneider, 2007.

[3] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

3.2 TYPE 4011. UPS LOSSES BASED ON MANUFACTURER PROPERTIES

An Uninterruptible Power Supply is a combinations of power converters, switches and energy storage media, e.g. batteries, that form a power supply system, guaranteeing ongoing supply to the load in case of a supply voltage failure. At the same time, voltage and frequency remain within the static and dynamic limits defined by the load. The international product standard IEC 62040-3 [1] classifies UPS into classes 1, 2 or 3 depending on the load limits.

Type 4011 is an empirical model for UPS. The model uses a mathematical equation, based on empirical coefficients, to describe the operational losses of a UPS. The model doesn't take into account the UPS battery. Therefore, the coefficients summarize the losses due to the double conversion, AC/DC and DC/AC, realized by the UPS converters. These coefficients can be deduced, from the efficiency curve, following the data regression technique described by Avelar, V. et al [2]. Usually, manufacturers provide the UPS efficiency at full load, but not the entire efficiency curve. However, the efficiency curve can be generated with the web tool created by Infineon, IPOSIM [3]. In this tool, it's possible to simulate the devices that generate the UPS losses, such as different types of power converters.

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| C_F | [kW] | No load losses coefficient. |
| C_P | [kW] | Proportional coefficient. |
| C_Q | [kW] | Square – law losses coefficient. |
| ζ_{UPS} | [kW] | Power losses of the UPS. |
| E_{ffUPS} | [%] | Efficiency of the UPS. |
| LF | [-] | Load factor of the UPS. |

| | | |
|-----------|--------|----------------------------------|
| N | $[-]$ | Number of UPS in parallel. |
| P_{in} | $[kW]$ | Power from grid side of the UPS. |
| P_N | $[kW]$ | Nominal power of the UPS. |
| P_{out} | $[kW]$ | Power to load side of the UPS. |

MATHEMATICAL DESCRIPTION

The component calculates the electrical losses (ζ_{UPS}), due to the double conversion of current inside the UPS, based on the load factor (LF) and three losses coefficients (C_F , C_P and C_Q).

The load factor is the percentage between the power to the load side of the UPS (P_{out}) and the nominal power of the UPS (P_N), equation (1).

The losses coefficients can be obtained from the efficiency curve, as is shown in Avelar, V. et al [1]. In order to create the efficiency curve the web tool IPOSIM [2], have been used. In this tool a two level bidirectional converter, with different amperage, has been simulated. These simulations allow us to deduce the values of the losses coefficients shown in Table 1. These coefficients are:

- No load losses coefficient (C_F): describes the UPS standby losses, losses at 0% load, attributable to powering such things as: capacitors, logic boards and communication cards. These losses are independent of the load.
- Proportional losses coefficient (C_P): As more power is added to the UPS, a larger amount of power will be flowing by various components in its power path, thus losses will increase. This coefficient, describes the losses that grow linearly with the load factor.
- Square-law losses coefficient (C_Q): As more power is added to the UPS, more current flows through its components. This causes losses in the UPS with the square of the current. This coefficient, describes the losses that grow in a quadratic way with the load factor.

Internally, the type divides the power to load side of the UPS by the number of UPS in parallel (N). At the end of the time step, in order to know the total power demanded from grid side of the UPS (P_{in}), the type multiplies the power to load side and the power losses of the UPS (ζ_{UPS}) by the number of Ups in parallel.

Therefore, the model considers the four following equations to compute the electrical losses of the UPS components.

Load factor of the UPS:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (1)$$

Power losses of the UPS:

$$\zeta_{UPS} = (C_F + C_P \cdot LF + C_Q \cdot LF^2) \quad [kW] \quad (2)$$

Power from grid side of the UPS:

$$P_{in} = P_{out} + \zeta_{UPS} \quad [kW] \quad (3)$$

Efficiency of the UPS:

$$E_{ffUPS} = \left(\frac{P_{out}}{P_{in}} \right) \cdot 100 \quad [\%] \quad (4)$$

ADDITIONAL INFORMATION

Different values for the UPS parameters are in Table 1, classified by load sizes. Notice that the values of the coefficients are given considering the double conversion, AC/DC and DC/AC, and simple conversion, AC/DC. If the user wants to simulate a UPS, use the double conversion values. If the user wants to simulate a converter, use the simple conversion values. These parameters have been obtained with the information extracted from the aforementioned tool [2].

Table 2 Coefficients values for different types of UPS [2]

| UPS converters type | Load [kW] | P_N [kW] | C_F [kW] | C_P [kW] | C_Q [kW] |
|--------------------------------------|-------------------------|------------|------------|------------|------------|
| <u>AC/AC</u> double conversion | <u>UPS1</u> : 0<L>39 | 42.662 | 0.01 | 0.4542 | 0.54289 |
| | <u>UPS2</u> : 39<L>193 | 203.798 | 0.01 | 2.2765 | 2.7424 |
| | <u>UPS3</u> : 193<L>643 | 709.546 | 0.01 | 8.1788 | 7.6633 |
| <u>AC/DC</u> simple conversion | <u>UPS1</u> : 0<L>39 | 42.662 | 0.01 | 0.2271 | 0.27144 |
| | <u>UPS2</u> : 39<L>193 | 203.798 | 0.01 | 1.1383 | 1.3712 |
| | <u>UPS3</u> : 193<L>643 | 709.546 | 0.01 | 4.0894 | 3.8316 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the UPS (*kW*)

Power send to the load connected at the UPS. This power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the UPS (*kW*)

Electrical losses associated with the operability of the UPS converters.

- Power from grid side of the UPS (*kW*)

Power feed to the UPS in order to satisfy the load demand. This power cannot exceed the nominal power of the component.

- Load factor of the UPS (-)

This value defines the percentage of the total capacity at which the UPS is working, 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the UPS (%)

Efficiency value of the UPS.

Parameters are described below:

- No load losses coefficient (kW)

Describes the UPS standby losses.

- Proportional losses coefficient (kW)

Describes the UPS losses that grow linearly with the load factor.

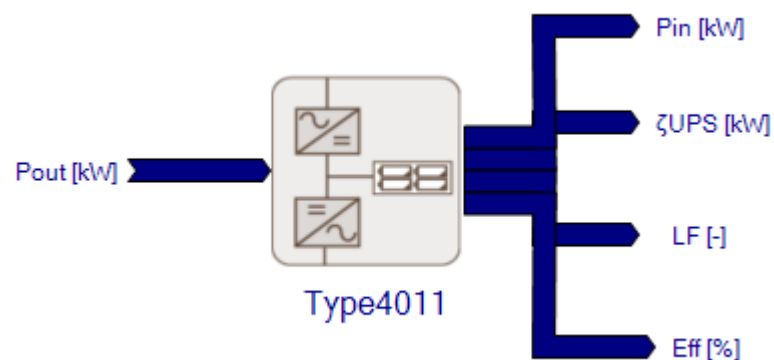
Square-law losses coefficient (kW) Describes the UPS losses that grow with the load factor in a quadratic way.

- Nominal power of the UPS (kW)

Nominal power defines the maximum power that can flow through the UPS.

- Number of UPS in parallel (-)

Number of UPS installed in parallel.



Graphic 6 Scheme of type 4011

REFERENCES

- [1] International Standard, IEC 62040-3, Uninterruptible power systems (UPS), PART 3: Method of specifying the performance and test requirements, First edition, 1999-2003.
- [2] Avelar, V. Making Large UPS Systems More Efficient, White paper #108, APC, Schneider, 2007.
- [3] IPOSIM, Web based simulation tool by Infineon.
<https://infineon.UPSsim.com/common/>

3.3 TYPE 4015. UPS DETAILED

An Uninterruptible Power Supply is a combinations of power converters, switches and energy storage media, e.g. batteries, that form a power supply system, guaranteeing ongoing supply to the load in case of a supply voltage failure. At the same time, voltage and frequency remain within the static and dynamic limits defined by the load. The international product standard IEC 62040-3 [1] classifies UPS into classes 1, 2 or 3 depending on the load limits.

Type 4015 is a detailed model for a UPS. The component works with two kinds of battery models: Lead-Acid and Li-Ion. These models are based in the ones developed by Tremblay, O. et al [2]. In order to adapt the Tremblay models to a UPS model, a couple of functions and internal controllers are added. These functions and controls cause losses and current limitations due to the UPS converters.

NOMENCLATURE

| | | |
|---------------|-------|------------------------------------------------------|
| A | [V] | Exponential zone amplitude. |
| C_F | [kW] | Converter no load losses coefficient. |
| C_P | [kW] | Converter proportional losses coefficient. |
| C_Q | [kW] | Converter square – law losses coefficient. |
| C_{par} | [–] | Battery cells in parallel. |
| C_{ser} | [–] | Battery cells in serie. |
| ζ_{C1} | [kW] | Losses of the converter in the grid side of the UPS. |
| ζ_{C2} | [kW] | Losses of the converter in the load side of the UPS. |
| ζ_{UPS} | [kW] | UPS losses. |
| E | [kWh] | Energy to or from battery. |
| E_0 | [V] | Battery constant voltage. |
| Eff_{UPS} | [%] | UPS efficiency. |

| | | |
|--------------|--------------|---------------------------------------------------------|
| i | [A] | Battery discharge current. |
| $i_{C1,out}$ | [kW] | Current from the converter in the grid side of the UPS. |
| I_{in} | [A] | Current from grid side of the UPS. |
| I_{out} | [A] | Current to load side of the UPS. |
| i_t | [A] | Current flowing to or from battery. |
| K | [Ω] | Battery polarization resistance. |
| kp | [–] | Proportional controller. |
| N | [–] | Number of UPS in parallel. |
| P | [kW] | Power to or from battery. |
| $P_{C1,out}$ | [kW] | Power from the converter in the grid side of the UPS. |
| $P_{N,C}$ | [kW] | Nominal power of converters. |
| P_{in} | [kW] | Power from grid side of the UPS. |
| P_{out} | [kW] | Power to load side of the UPS. |
| Q_{exp} | [Ah] | Battery capacity at the end of the exponential zone. |
| Q_{max} | [Ah] | Battery maximum capacity. |
| Q_{nom} | [Ah] | Battery capacity at the end of the nominal zone. |
| Qt | [Ah] | Battery capacity. |
| R | [Ω] | Battery internal resistance. |
| SOC | [%] | Actual state of charge of the battery. |
| SOC_0 | [%] | Initial state of charge of the battery. |
| SOC_{ref} | [%] | Reference state of charge of the battery. |
| U | [V] | Battery voltage. |
| U_{rch} | [V] | Battery polarization resistance during charge. |
| U_{rch} | [V] | Battery polarization resistance during discharge. |

| | |
|-------------------|-----------------------------------------------------|
| $U_{exp,bat}$ [V] | Battery exponential voltage. |
| U_{exp} [V] | Battery voltage at the end of the exponential zone. |
| U_{full} [V] | Battery voltage at fully charge. |
| U_{in} [V] | Voltage from grid side of the UPS. |
| U_{max} [V] | Battery maximum voltage. |
| U_{min} [V] | Battery minimum voltage. |
| U_{nom} [V] | Battery voltage at the end of the nominal zone. |
| U_{out} [V] | Voltage to load side of the UPS. |
| U_{pol} [V] | Battery polarization voltage. |
| ΔCap [–] | Enhancement of battery capacity. |
| ΔE [kWh] | Internal energy change of the battery. |
| Δt [h] | Simulation time step. |

MATHEMATICAL DESCRIPTION

The characteristic discharge curve given by the manufacturers [3] provides the battery parameters, through the discharge current (i) and three points of the curve. From these points is possible to extract the fully charged voltage (U_{full}), the voltage and capacity at the end of the exponential zone (Q_{exp}, U_{exp}), the voltage and capacity at the end of the nominal zone, when the voltage starts to drop abruptly, (Q_{nom}, U_{nom}) and the maximum capacity (Q_{max}). Typically, the internal resistance (R) is given too. These values must be specified for a battery cell, and internally the type adjust this cell values to the battery values. The voltage values are multiplied by the number of battery cells in serie (C_{ser}), while capacity and current values are multiplied by the number of battery cells in parallel (C_{par}). Moreover, the internal resistance is also adjusted by multiplying and dividing it by the number of cells in series and the number of cells in parallel, respectively. From these parameters and the system of equations (1), (2), and (3) the type computes the rest of the battery parameters which are: battery

constant voltage (E_0), polarisation resistance (K), and exponential zone amplitude (A).

Battery voltage at fully charge:

$$U_{full} = E_0 - R \cdot i + A \quad [V] \quad (1)$$

Battery voltage at the end of the exponential zone:

$$U_{exp} = E_0 - K \cdot \frac{Q_{max}}{Q_{max} - Q_{exp}} \cdot (Q_{exp} + i) - R \cdot i + A \exp\left(\frac{-3}{Q_{exp}} \cdot Q_{exp}\right) \quad [V] \quad (2)$$

Battery voltage at the end of the nominal zone:

$$U_{nom} = E_0 - K \cdot \frac{Q_{max}}{Q_{max} - Q_{nom}} \cdot (Q_{nom} + i) - R \cdot i + A \exp\left(\frac{-3}{Q_{exp}} \cdot Q_{nom}\right) \quad [V] \quad (3)$$

The rest of UPS parameters is related with the converters characteristics, such as the converter nominal power ($P_{N,C}$), the no load (C_F), proportional (C_P), and square-law (C_Q) losses coefficients, which are already described in the documentation of Type 4011.

Additionally, the type includes an extra parameter called enhancement (ΔCap), which internally multiplies the number of battery cells in parallel. We will not modify the battery characteristics as this value is set to the default value 1. Otherwise, we will be increasing or decreasing the number of battery cells in parallel, which is equivalent to increase or decrease the energy capacity of the battery. This parameter is introduced in order to help the user in the parametric analysis, related with the energy storage of the battery. Once the UPS parameters are known, it is possible to analyze the UPS behaviour.

Firstly, it is necessary to know if the UPS will be charging or discharging energy, this behaviour is governed by the input value called reference state of charge (SOC_{ref}). If the SOC_{ref} is higher than SOC , the UPS starts to store energy. In contrast, if the SOC_{ref} is lower than SOC , a discharge phase starts. This operation is computed using equation (4), where the sign of current (i_t) will define if UPS is charging or discharging energy. An internal control will ensure that the result from equation (4) does not exceed the nominal current of the UPS converters.

Current from or to UPS battery:

$$i_t = (100 \cdot (1 - \frac{Qt}{Q_{max}})^* - SOC_{ref}) \cdot kp \quad [A] \quad (4)$$

$$\text{Where: } kp = 1.6 \cdot \frac{C_{par}}{30}$$

*At the initial time step the initial UPS capacity (Qt_0) is calculated as shown in equation (5).

The expected output power (P_{out}) and the output voltage (U_{out}) are used as input values to the converter function. Such a function computes the contributions of losses of the converter placed downstream of the battery (ζ_{c2}). This converter function is identical for both UPS converters, and it is described in the documentation of Type4011.

The initial UPS capacity (Qt_0) and the capacity at the end of time step ($Qt_{t+\Delta t}$) due to the current flowing from or to the battery are computed using equations (5) and (6), respectively. The associated SOC to the UPS capacity, at the end of time step, is computed using equation (7). Furthermore, an internal control will check that the SOC does not exceed the maximum value (100%) or drop below zero.

Initial battery capacity:

$$Qt_0 = (1 - \frac{SOC_0}{100}) \cdot Q_{max} \quad [Ah] \quad (5)$$

Battery capacity at the end of time step:

$$Qt_{t+\Delta t} = Qt_t^* + (i_t \cdot \Delta t) \quad [Ah] \quad (6)$$

*At the initial time step $Qt_t = Qt_0$

Battery state of charge at the end of time step:

$$SOC_t = 100 * (1 - \frac{Qt_t}{Q_{max}}) \quad [\%] \quad (7)$$

The model computes the UPS voltage (U) via equation (8). By adding different voltages functions and the parameter battery voltage (E_0), These functions are: the polarization voltage (U_{pol}), the polarization resistance, which will be different between charge (U_{rch}) and discharge (U_{rch}), and the exponential voltage

$(U_{exp,bat})$, which differs for each type of battery. These functions are calculated using equations (9), (10), (11), (12) and (13) described below. Additionally, a control over the voltage is applied in order to ensure that this does not exceed the maximum or minimum (U_{max}, U_{min}) values, equations (14) and (15), respectively.

Battery voltage:

$$U_t = U_{pol,t} + U_{r_{dch},t} + U_{r_{ch},t} + U_{exp,bat,t} + E_0 \quad [V] \quad (8)$$

Where bat depends on the type of battery selected, Li ion or Lead Acid.

Battery polarization voltage:

$$U_{pol,t} = -K \cdot \frac{Q_{max}}{Q_{max} - Qt_t} \cdot Qt_t \quad [V] \quad (9)$$

Battery polarization resistance (discharge):

$$U_{r_{dch},t} = -sign \cdot K \cdot i_t \cdot \frac{Q_{max}}{Q_{max} - Qt_t} \quad [V] \quad (10)$$

$$\text{Where: } \begin{cases} sign = 1 & \text{If } SOC_t > SOC_{ref} \\ sign = 0 & \text{If } SOC_t < SOC_{ref} \end{cases}$$

Battery polarization resistance (charge):

$$U_{r_{ch},t} = -sign \cdot K \cdot i_t \cdot \frac{Q_{max}}{Qt_t + Q_{max} \cdot 0.1} \quad [V] \quad (11)$$

$$\text{Where: } \begin{cases} sign = 0 & \text{If } SOC_t > SOC_{ref} \\ sign = 1 & \text{If } SOC_t < SOC_{ref} \end{cases}$$

Li Ion Battery exponential voltage:

$$U_{exp,t,Li\ ion} = A \exp\left(\frac{-3}{Q_{exp}} \cdot Qt_t\right) \quad [V] \quad (12)$$

Lead Acid Battery exponential voltage:

$$U_{exp,t,Lead\ Acid} = (sign \cdot A \cdot U_{exp,t-\Delta t}^*) \cdot |i_t| \cdot \frac{-3}{3600} \cdot (\Delta t \cdot 3600) + U_{exp,t-\Delta t}^* [V] \quad (13)$$

$$^* \text{At the initial time step } U_{exp,t-\Delta t}^* = A \exp\left(\frac{-3}{Q_{exp}} \cdot \left(1 - \frac{SOC_0}{100}\right) \cdot Q_{max}\right)$$

Maximum battery voltage:

$$U_{max,t} = 2 \cdot E_0 \quad [V] \quad (14)$$

Minimum battery voltage:

$$U_{min,t} = i_t \cdot R \quad [V] \quad (15)$$

Finally, equation (16) shows that the voltage is corrected in order to consider the drop of voltage due to the internal resistance of the battery. As the new voltage and current of UPS are known, the power delivered or consumed by UPS can be computed (P) through equation (17).

Drop of voltage due to battery losses:

$$U_t = U_t - i_t \cdot R \quad [V] \quad (16)$$

Power to or from battery:

$$P_t = \frac{(U_t \cdot i_t)}{1000} \quad [kW] \quad (17)$$

Kirchhoff's law computes the current flowing by the converter upstream the battery. This current ($i_{C1,out}$) and the battery voltage (U) provide the expected output power from this converter ($P_{C1,out}$). The converter function computes the losses due to this converter (ζ_{C1}) and the expected input power (P_{in}) to the. Therefore, equations (18) and (19) calculate the total losses inside the UPS (ζ_{UPS}) and the efficiency of it (Eff_{UPS}). The result from equation (17) and the time step of TRNSYS simulation (Δt) provide the energy of the UPS. The storage of this value between time steps allows us to compute the internal energy change of the battery (ΔE) via equation (20).

UPS losses:

$$\zeta_{UPS,t} = \frac{\zeta_{C1} + \zeta_{C2} + |i_t|^2 \cdot R}{1000} \quad [kW] \quad (18)$$

Efficiency of UPS:

$$Eff_{UPS,t} = \frac{P_{out,t}}{(P_{out,t} + \zeta_{UPS,t})} \cdot 100 \quad [kW] \quad (19)$$

Internal energy change of battery:

$$\Delta E_t = E_{t-1} + E_t \quad [kWh](20)$$

Finally, it is worth noticed that all the operations listed above are computed for one UPS and the results are multiplied by the number of units (N) connected in parallel, as equitable load distribution between UPSs is assumed..

ADDITIONAL INFORMATION

As an example a set of values for UPS parameters are listed in Table 1 and 2, below. The values in Table 1, have been extracted from the discharge curve of a Lead-Acid from Panasonic manufacturer [3]. Moreover, Table 2 contains the rest of UPS parameters, where these are given depending on the load demand necessary to satisfy. The parameters regarding the converters characteristics have been deduced in the same way as for Type4011, using the web tool IPOSIM [4]. The battery parameters listed in Table 2, are given for a UPS that will achieve, at maximum current, 50% of SOC in 15 min.

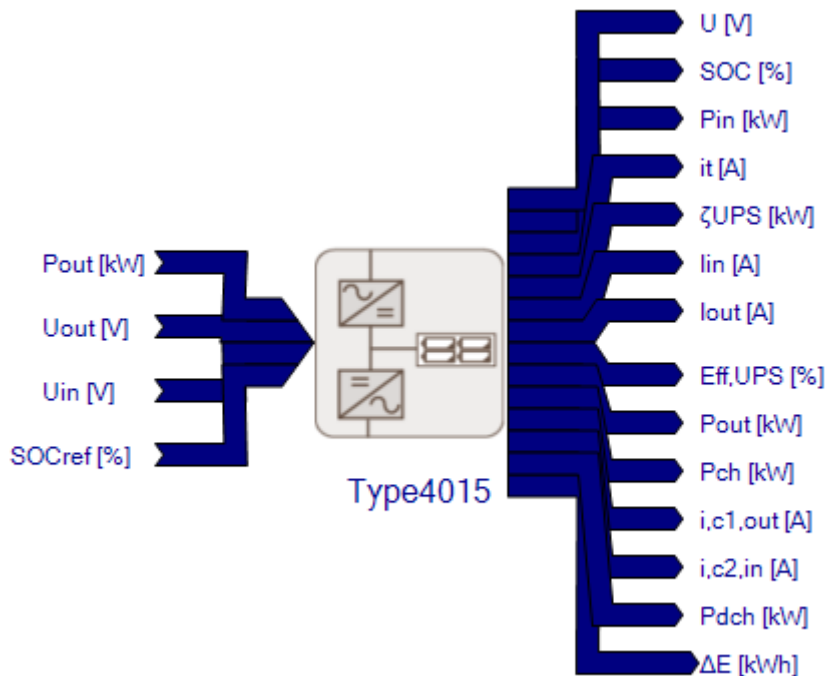
Table 3 Lead-Acid battery parameters [3]

| Battery Parameters | |
|--------------------|------|
| U_{full} [V] | 1.39 |
| U_{exp} [V] | 1.28 |
| U_{nom} [V] | 1.18 |
| Q [Ah] | 1.80 |
| Q_{nom} [Ah] | 1.60 |
| i [A] | 1.37 |

Table 4 UPS parameters for different load demand [4]

| Load [kW] | UPS | | | | | |
|-----------|--------------------|------------------|-----------------------------|--------------|---------------|---------------|
| | Battery Parameters | | AC/DC Converters Parameters | | | |
| | C_{set} [-] | C_{par} [-] | $P_{N,C}$ [kW] | C_F [-] | C_P [kW] | C_Q [kW] |
| 0<L>39 | 400 | 30 | 42 | 0.01 | 0.2271 | 0.27144 |
| 39<L>193 | 400 | 120 | 203 | 0.01 | 1.1383 | 1.37120 |
| 193<L>643 | 400 | 435 | 709 | 0.01 | 4.0894 | 3.83160 |

INPUTS, OUTPUTS AND PARAMETERS



Graphic 7 Scheme of type 4011

Inputs are described below:

- Power to load side of the UPS (kW)

Power send to the load connected at the PDU. This amount of power cannot exceed the nominal power of the component.

- Voltage to load side of the UPS (V)

Distribution voltage at the load side of the UPS.

- Voltage from grid side of the UPS (V)

Distribution voltage at the grid side of the UPS.

- Reference SOC (%)

Desired state of charge of the UPS battery. Can be used as a control signal in order to charge or discharge energy from the battery.

Outputs are described below:

- Battery voltage (*V*)
Voltage delivered by the UPS battery.
- SOC (%)
State of charge of the UPS battery at the end of the time step.
- Power from grid side of the UPS (*kW*)
Power feed to the UPS in order to satisfy the load demand. This power cannot exceed the nominal power of the component.
- Battery current (*amperes*)
Current flowing to or from UPS battery.
- UPS losses (*kW*)
Electrical losses associated with the operability of the component.
- Current from grid side of the UPS (*amperes*)
- Current to load side of the UPS (*amperes*)
- Efficiency (%)
Efficiency value of the UPS.
- Power to load side of the UPS (*kW*)
Power send to the load connected at the UPS. This amount of power cannot exceed the nominal power of the component.
- Battery charge power (*kW*)
Power consumption used to charge the UPS battery.
- Converter -1 output current (*amperes*)
Current flowing from the converter, placed upstream of the UPS battery, to the UPS battery.

- Converter -2 input current (*amperes*)
Current flowing from the UPS battery to the converter placed downstream of the UPS battery.
- Battery discharge power (*kW*)
Power delivered by the UPS battery.
- Internal energy change of the battery (*kWh*)
Variation of energy inside the UPS battery.

Parameters are described below:

- Battery cells in series (-)
Number of battery cells in series.
- Battery cells in parallel (-)
Number of battery cells in parallel.
- Initial SOC (%)
Initial state of charge of UPS batteries.
- Type (-)
Type of batteries used by the UPS (1-Lead Acid, 2-Li ion battery).
- Voltage per cell when fully charged (*V*)
Voltage per cell when the battery is fully charged.
- Voltage at the end of the exponential zone (*V*)
Cell voltage before start the exponential zone.
- Nominal voltage of the battery cell (*V*)
Voltage per cell before the abruptly drop of voltage.
- Maximum capacity per cell (*Ah*)
Maximum capacity of a battery cell.

- Nominal capacity per cell (*Ah*)
Cell capacity before the voltages starts to drop abruptly.
- Maximum current per cell (*amperes*)
Maximum current through battery cell.
- Converters no load losses coefficient (*kW*)
Describe the converters losses in standby.
- Converters proportional losses coefficient (*kW*)
Describe the converters losses that grow linearly with the load factor.
- Converter square-law losses coefficient (*kW*)
Describe the converters losses that grow quadratically with the load factor.
- Converter nominal power (*kW*)
The converter nominal power defines the maximum power through converters.
- Number of UPS in parallel (-)
Defines the number of UPS units connected in parallel. It's assumed that the load is split equitably between them.
- Enhancement (%)
Parameter used to increase the energy capacity of the UPS battery. Internally this parameter multiplies the number of battery cells in parallel.

Default value, 1, means that no enhancement is done over the initial battery energy capacity.

REFERENCE

- [1] International Standard, IEC 62040-3, Uninterruptible power systems (UPS), PART 3: Method of specifying the performance and test requirements, First edition, 1999-2003.
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4. POWER DISTRIBUTION UNIT (PDU)

4.1 TYPE 4002. PDU BASED ON LOAD FACTOR DEPENDENCE

The Power Distribution Unit (from now PDU) is a device fitted with multiple outputs designed to distribute electric power. This unit includes main breakers, individual breakers and power monitoring panels to show and ensure the properly energy distribution to each of the electrical devices connected to the PDU.

Type 4002 is an empirical model for a PDU. The model uses a mathematical equation, based on empirical coefficients, to describe the operational losses of a PDU. These coefficients can be deduced, if the efficiency curve is known, following the data regression technique described by Avelar, V. et al [1]. As an example, a set of values for the coefficients can be found in the tool provided by Schneider [2].

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| C_F | [-] | No load losses coefficient. |
| C_P | [-] | Proportional losses coefficient. |
| C_Q | [-] | Square – law losses coefficient. |
| C_S | [-] | Sizing coefficient. |
| ζ_{PDU} | [kW] | Power losses of the PDU. |
| Eff_{PDU} | [%] | Efficiency of the PDU. |
| LF | [-] | Load factor of the PDU. |
| P_{in} | [kW] | Power from grid side of the PDU. |
| P_N | [kW] | Nominal power of the PDU. |
| P_{out} | [kW] | Power to load side of the PDU. |

P_{Ref} [kW] Reference power.

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to a PDU (ζ_{PDU}) based on the nominal power (P_N), load factor (LF) and three losses coefficients (C_F , C_P and C_Q).

The type computes the nominal power of the PDU multiplying the sizing coefficient (C_S) by the reference power of the system (P_{Ref}), equation (1). The load factor is the percentage between the power to the load side of the PDU (P_{out}) and the nominal power of the PDU, equation (2). The losses coefficients can be obtained from the efficiency curve provided by manufacturers, as is shown in Avelar, V. et al [1]. These coefficients are:

- No load losses coefficient (C_F): describes the PDU standby losses, losses at 0% load, attributable to powering such things as: logic boards and communication cards. These losses are independent of the load.
- Proportional losses coefficient (C_P): As more power is added to the PDU, a larger amount of power will be flowing by various components in its power path, thus losses will increase. This coefficient, describes the losses that grow linearly with the load factor.
- Square-law losses coefficient (C_Q): As more power is added to the PDU, more current flows through its components. This causes losses in the PDU with the square of the current. This coefficient, describes the losses that grow quadratically with the load factor.

Therefore, the model considers the five following equations to compute the electrical losses of PDU components.

Nominal power of the PDU:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Load factor of the PDU:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (2)$$

Power losses of the PDU:

$$\zeta_{PDU} = P_N \cdot C_F + P_N \cdot C_P \cdot LF + P_N \cdot C_Q \cdot LF^2 \quad [kW] \quad (3)$$

Power from grid side of the PDU:

$$P_{in} = P_{out} + \zeta_{PDU} \quad [kW] \quad (4)$$

Efficiency of the PDU:

$$Eff_{PDU} = \left(\frac{P_{out}}{P_{in}} \right) * 100 \quad [\%] \quad (5)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for Data Centre according to [2]. If the PDU is installed into a Data Centre the installed IT power must be taken as the reference power.

Table 5 Coefficients for different types of PDU [2].

| System | C_S | C_F | C_P | C_Q |
|--------------|-------|-------|-------|-------|
| PDU with STS | 2.5 | 0.011 | 0.009 | 0.005 |
| PDU | 2.5 | 0.011 | 0.000 | 0.005 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the PDU (*kW*)

Power send to the load connected at the PDU. This amount of power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the PDU (*kW*)

Electrical losses associated with the operation of the component.

- Power from the grid side of the PDU (*kW*)

Power feed to the PDU in order to satisfy the load demand. This power cannot exceed the nominal power of the component.

- Load factor of the PDU(-)

This value defines the percentage of the total capacity at which the PDU is working. A load factor of 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the PDU(%)

Efficiency value of PDU.

Parameters are described below:

- Sizing coefficient (-)

This coefficient is used to approximate the nominal power of the component. The nominal power is calculated multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- No load losses coefficient (-)

Describes the PDU standby losses.

- Proportional losses coefficient (-)

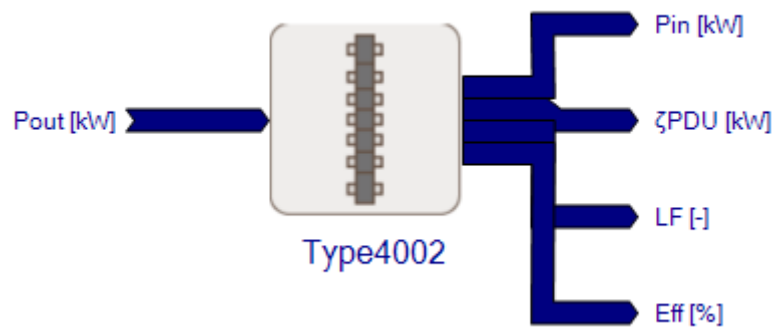
Describes the PDU losses that grow linearly with the load factor.

- Square-law losses coefficient (-)

Describes the PDU losses that grow quadratically with the load factor.

- Reference power (kW)

The reference power is the installed power of our system. If the PDU is installed into a Data Centre, the installed IT power must be taken as the reference power.



Graphic 8 Scheme of type 4002

REFERENCE

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5. WIRE

5.1 TYPE 4003. WIRE BASED ON LOAD FACTOR DEPENDENCE

A wire is used to carry electrical current from the power source to the load consumption, such as lighting and electrical machines. The losses of a wire depend on his operating current, the size and the length of it. Rasmussen, N. et al [1] quantifies, as a common design value, the wiring losses in a 1% of the power at full load.

Type 4003 is an empirical model for a wire. The model use a mathematical equation based on empirical coefficients to compute the losses in the wire. The material resistivity of wire dissipates current and generates losses in the form of heat. A coefficient describing the current dissipated through wire at different load factors, can be deduced following a data regression technique, similar to the work done by Avelar, V. et al [2]. As an example, values for the coefficients can be found in the tool provided by Schneider [3].

NOMENCLATURE

| | | |
|----------------|------|-----------------------------------|
| C_Q | [-] | Square – law losses coefficient. |
| C_S | [-] | Sizing coefficient. |
| ζ_{WIRE} | [kW] | Power losses of the wire. |
| Eff_{WIRE} | [%] | Efficiency of the wire. |
| LF | [-] | Load factor of the wire. |
| P_{in} | [kW] | Power from grid side of the wire. |
| P_N | [kW] | Nominal power of the wire. |
| P_{out} | [kW] | Power to load side of the wire. |

P_{Ref} [kW] Reference power.

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to a wire (ζ_{WIRE}), based on the nominal power (P_N), load factor (LF) and a losses coefficient (C_Q).

The type computes the nominal power of the wire multiplying the sizing coefficient (C_S) by the reference power of the system (P_{Ref}), equation (1). The load factor is the percentage between the power to the load side (P_{out}) and the nominal power of the wire, equation (2).

A wire generates losses, in a form of heat, due to the current dissipated. These losses are proportional to the square of current and are usually called as the Square-law losses (C_Q). As more power is demanded by the load, more current is flowing through wire, thus the losses increases. These losses can be characterized if the wire maximum current and resistivity are known.

The wire material is usually known thus, the wire resistivity can be known. Knowing the nominal power of the wire and the voltage distribution of the system, one can compute the wire maximum current. The losses will be the results of multiply the square of current by the wire resistivity. Therefore, increasing the current from zero to the maximum it's possible to deduce the wire losses at different load factors. Finally, as Avelar, V. et al [2] describes, plotting these losses on a graph and applying a data regression technique it's possible to obtain the value of the Square-law losses coefficient.

Nominal power of the wire:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Load factor of the wire:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (2)$$

Power losses of the wire:

$$\zeta_{WIRE} = P_N \cdot C_Q \cdot LF^2 \quad [kW] \quad (3)$$

Power from grid side of the wire:

$$P_{in} = P_{out} + \zeta_{WIRE} \quad [kW] \quad (4)$$

Efficiency of the wire:

$$Eff_{WIRE} = \left(\frac{P_{out}}{P_{in}} \right) * 100 \quad [\%] \quad (5)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for Data Centre according to [3]. If the wire is installed into a Data Centre, the installed IT power must be taken as the reference power.

Table 6 Coefficients for a wire [3].

| System | C_S | C_Q |
|--------|-------|-------|
| WIRE | 3.0 | 0.010 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the wire (*kW*)

Power send to the load connected at the wire. This amount of power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the wire (*kW*)

Electrical losses due to current dissipation.

- Power from grid side of the wire (*kW*)

Power feed to the wire in order to satisfy the load demand. This power cannot exceed the nominal power of the component.

- Load factor of the wire(-)

This value defines the percentage of the total capacity at which the wire is working. A load factor of 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the wire (%)

Efficiency value of wire.

Parameters are described below:

- Sizing coefficient (-)

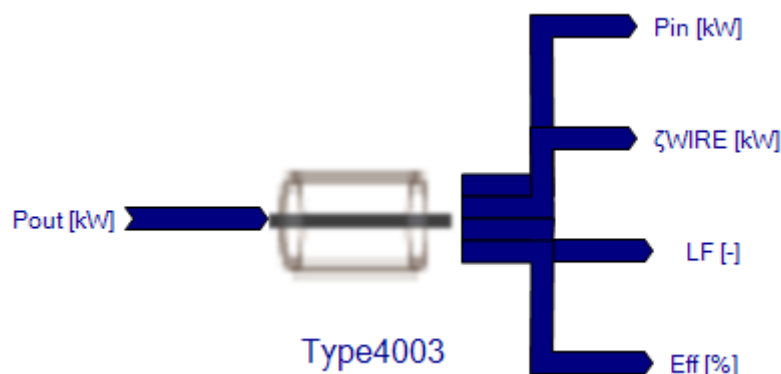
This coefficient is used to approximate the nominal power of the component. The nominal power is computed multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- Square-law losses coefficient (-)

Describes the wire losses that grow quadratically with the load factor.

- Reference power (kW)

The reference power is the installed power of our system. If the wire is installed into a Data Centre, the installed IT power must be taken as the reference power.



Graphic 9 Scheme of type 4003

REFERENCE

[1] Rasmussen, N. Spitels, J. A Quantitative Comparison of High Efficiency AC vs DC power distribution for Data Centers, White Paper #127, APC, Schneider, 2012.

[2] Avelar, V. Making Large UPS Systems More Efficient, White paper #108, APC, Schneider, 2007.

[3] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

5.2 TYPE 4010. WIRE BASED ON MANUFACTURER PROPERTIES

A wire is used to carry electrical current from the power source to the load consumption, such as lighting and electrical machines. The losses of a wire depend on his operating current, the size and the length of it. Rasmussen, N. et al [1] quantifies, as a common design value, the wiring losses in a 1% of the power at full load.

Type 4010 is an empirical model for wire. The model uses Joule's law to describe the operational losses of a wire. In order to apply Joule's law, it's necessary to know some characteristics of our wires, such as, diameter, length and material resistivity. Usually wires are done with copper, which has an electrical resistivity of $0.0172 \Omega \cdot \text{mm}^2$. The available wires diameters can be found in manufacturers catalogues, such as in [1]. Moreover, it's assumed a three phase wire configuration.

NOMENCLATURE

| | | |
|----------------|------|-----------------------------------|
| ζ_{WIRE} | [kW] | Power losses of the wire. |
| d | [mm] | Diameter of the wire. |
| Eff_{WIRE} | [%] | Efficiency of the wire. |
| I | [A] | Current to load side of the wire. |
| I_{NO} | [A] | Nominal current of the wire. |
| L | [m] | Length of the wire. |
| LF | [-] | Load factor of the wire. |
| N | [-] | Number of wires. |
| P_{in} | [kW] | Power from grid side of the wire. |
| P_{out} | [kW] | Power to load side of the wire. |
| P_{Ref} | [kW] | Reference power. |

$$R_{Mat} \quad \left[\frac{\Omega \cdot \text{mm}^2}{m} \right] \quad \text{Material electrical resistivity.}$$

$$R_{WIRE} \quad [\Omega] \quad \text{Wire resistivity.}$$

$$U_{out} \quad [V] \quad \text{Output voltage.}$$

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to Joule's effect in wires (ζ_{WIRE}), due to electrical power distribution. Joule's law determines the heat generated by an electrical current flowing through a conductor, in other words the electrical losses generated due to electrical resistivity (R_{Mat}). Therefore, knowing the wire resistivity (R_{WIRE}) and the current (I) flowing through it, one can compute the electrical losses. These losses will be multiplied by three in order to take into account the three phase configuration. The wire resistivity depends on their physical characteristics, diameter (d), length (L) and material resistivity, where diameter and material resistivity can be easily found in manufacturers catalogues and wire length will depend on our installation size. Thus, using the following formulas it's possible to compute the electrical losses of a wire. Notice that some of the following formulas, equation 2 and 4, are not used to compute wire losses but are added in order to control that the current to load side of the wire do not exceed its nominal current (I_{NO}).

Internally the type divides the power to load side of the wire by the number of wires (N). At the end of the time step, the type multiplies the power to load side (P_{out}) and the power losses of the wire by the number of wires in order to know the total power from grid side of the wire (P_{in}).

Wire resistivity:

$$R_{WIRE} = \frac{R_{Mat}}{\pi \cdot \frac{d^2}{4}} \quad [\Omega] \quad (1)$$

Nominal current of the wire:

$$I_{NO} = \frac{P_{Ref} \cdot 1000}{U_{out} \cdot \sqrt{3}} \quad [A] \quad (2)$$

Current to load side of the wire:

$$I = \frac{P_{out} \cdot 1000}{U_{out} \cdot \sqrt{3}} \quad [A] \quad (3)$$

Load factor of the wire:

$$LF = \frac{I}{I_{NO}} \quad [-] \quad (4)$$

Power losses of the wire:

$$\zeta_{WIRE} = \frac{R_{WIRE} \cdot I^2 \cdot 3}{1000} \quad [kW] \quad (5)$$

Power from gird side of the wire:

$$P_{in} = P_{out} + \zeta_{WIRE} \quad [kW] \quad (6)$$

Efficiency of the wire:

$$E_{ff} = \left(\frac{P_{out}}{P_{in}} \right) \cdot 100 \quad [\%] \quad (7)$$

ADDITIONAL INFORMATION

Different values for wire diameter are given, classified by load size. These diameters have been collected from a catalogue of the manufacturer [1].

Table 7 Diameter values for WIRE [1].

| Load [kW] | d [mm] | U_{out} [V] |
|-----------------|----------|---------------|
| Wire: 0<L>39 | 4.57 | 400 |
| Wire: 39<L>193 | 16.76 | 400 |
| Wire: 193<L>643 | 24.89 | 400 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the wire (kW)

Power send to the load connected at the wire. This amount of power cannot give a current that exceeds the nominal current of the component.

Outputs are described below:

- Power losses of the wire (kW)

Electrical losses associated with the Joule's effect.

- Power from grid side of the wire (kW)

Power feed to the wire in order to satisfy the load demand. This amount of power cannot give a current that exceeds the nominal current of the component.

- Load factor of the wire (-)

This value defines the percentage of the total capacity at which the wire is working. A load factor of, 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the wire (%)

Efficiency of the component (%)

- Current to load side of the wire (A)

Current send to the load connected at the wire. This current cannot exceed the nominal current of the wire.

- Nominal current of the wire (A)

The nominal current defines the maximum current that can flow through the wire.

Parameters are described below:

- Length of the wire(m)

Length of the wire to be analysed.

- Diameter of the wire(mm)

Diameter of the wire to be analysed.

- Material resistivity (-)

Material electric resistivity. Default value is for a wire made of copper.

- Output voltage (V)

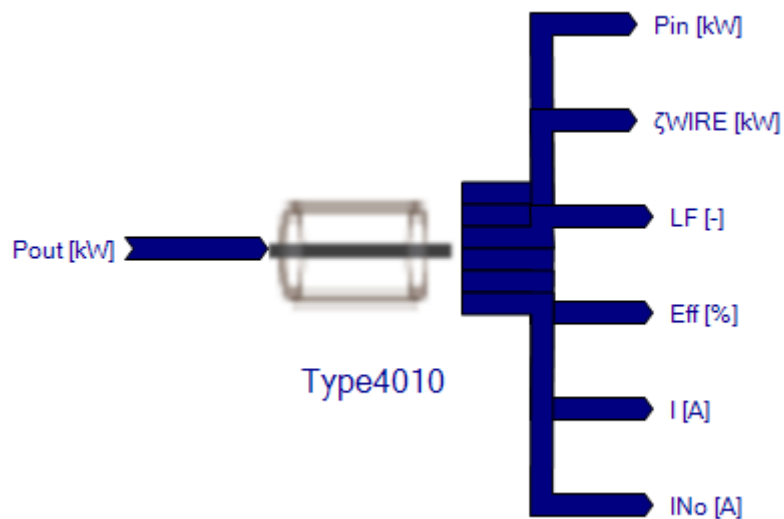
Distribution voltage

- Reference power (kW)

The reference power is the installed power of our system. If the wire is installed into a Data Centre, the installed IT power must be taken as the reference power.

- Number of wires (-)

Number of wires installed in parallel.



Graphic 10 Scheme of type 4010

REFERENCES

- [1] General Cable, Model XHHW-2 CT, page 7. General Cable. Available online: <http://www.generalcable.com/NR/rdonlyres/48274175-9228-4BB5-90EF-DBBC9289C1DB/0/BuildingWireCopper.pdf>

6. SWITCHGEAR (SWG)

6.1 TYPE 4004. SWG BASED ON LOAD FACTOR DEPENDENCE

A switchgear (from now SWG) is used to control protect and isolate electrical equipment, connecting and disconnecting the electrical equipment from the electrical source in case of power failures or inappropriate electrical power supply conditions. Therefore, this component is directly linked to the reliability of the electricity supply.

Type 4004 is an empirical model for SWG. The model uses a mathematical equation, based on empirical coefficients, to describe the operational losses of switchgear. The model takes into account the losses due to the inherent SWG electrical resistance and neglects the losses due to leakage currents. As an example, values for the coefficients can be found in the tool provided by Schneider [1].

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| C_Q | [-] | Square – law losses coefficient. |
| C_S | [-] | Sizing coefficient. |
| ζ_{SWG} | [kW] | Power losses of the SWG. |
| Eff_{SWG} | [%] | Efficiency of the SWG. |
| LF | [-] | Load factor of the SWG. |
| P_{in} | [kW] | Power from grid side of the SWG. |
| P_N | [kW] | Nominal power of the SWG. |
| P_{out} | [kW] | Power to load side of the SWG. |
| P_{Ref} | [kW] | Reference power. |

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to a SWG (ζ_{SWG}), based on the nominal power (P_N), load factor (LF) and a losses coefficient (C_Q).

The type calculates the nominal power of the SWG multiplying the sizing coefficient (C_S) by the reference power of the system (P_{Ref}), equation (1). The load factor is the percentage between the power to the load side (P_{out}) and the nominal power of the SWG, equation (2).

If the SWG is open, the losses are generated due to leakage currents which are neglected in this model. In contrast, if the SWG is close the losses are generated due to the inherent SWG electrical resistance. These losses are proportional to the square of current and are usually called as the Square-law losses. As more power is demanded by the load, more current is flowing through SWG, thus the losses increases. These losses can be characterized if the SWG nominal current and resistivity are known.

The losses will be the results of multiply the square of current by the SWG resistivity. Therefore, increasing the current from zero to the nominal it's possible to deduce the SWG losses, at different load factors. Finally, as Avelar, V. et al [2] describes, plotting these losses on a graph and applying a data regression technique it's possible to obtain the value of the Square-law losses coefficient.

Nominal power of the SWG:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Load factor of the SWG:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (2)$$

Power losses of the SWG:

$$\zeta_{SWG} = P_N \cdot C_Q \cdot LF^2 \quad [kW] \quad (3)$$

Power from grid side of the SWG:

$$P_{in} = P_{out} + \zeta_{SWG} \quad [kW] \quad (4)$$

Efficiency of the SWG:

$$Eff_{SWG} = \left(\frac{P_{out}}{P_{in}} \right) * 100 \quad [\%] \quad (5)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for Data Centre according to [1]. If the SWG is installed into a Data Centre, the total installed power (IT + cooling) must be taken as the reference power.

Table 8 Coefficients for SWG [1].

| System | C_S | C_Q |
|------------|-------|-------|
| Switchgear | 2.0 | 0.010 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the SWG (*kW*)

Power send to the load connected at the SWG. This amount of power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the SWG (*kW*)

Electrical losses due to the electrical resistance.

- Power from grid side of the SWG (*kW*)

Power feed to the SWG in order to satisfy the load demand. This power cannot exceed the nominal power of the component.

- Load factor of the SWG (-)

This value defines the percentage of the total capacity at which the SWG is working. A load factor of 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the SWG(%)

Efficiency value of the component.

Parameters are described below:

- Sizing coefficient (-)

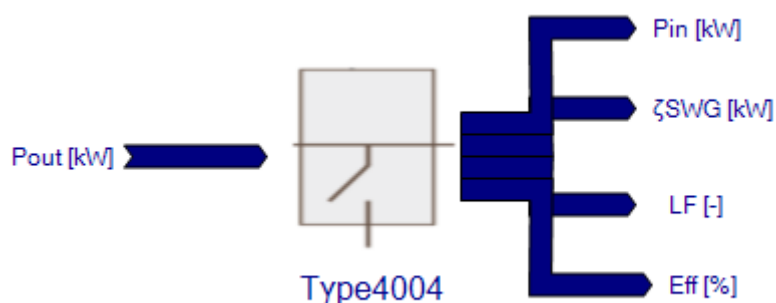
This coefficient is used to approximate the nominal power of the component. The nominal power is computed multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- Square-law losses coefficient (-)

Describes the SWG losses that grow quadratically with the load factor.

- Reference power (kW)

The reference power is the installed power of our system. If the SWG is installed into a Data Centre, the total installed power (IT + cooling) must be taken as the reference power.



Graphic 11 Scheme of type 4004

REFERENCE

[1] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

[2] Avelar, V. Making Large UPS Systems More Efficient, White paper #108, APC, Schneider, 2007.

6.2 TYPE 4009. SWG BASED ON MANUFACTURER PROPERTIES

A switchgear (from now SWG) is used to control protect and isolate electrical equipment, connecting and disconnecting the electrical equipment from the electrical source in case of power failures or inappropriate electrical power supply conditions. Therefore, these types of units are directly linked to the reliability of the electricity supply.

Type 4009 is an empirical model for SWG. The model use a mathematical equation, based on empirical coefficients, to describe the operational losses of switchgear, as is shown in the catalogue from manufacturer [1]. Furthermore, the coefficients used by the model can be found in the catalogue already mentioned [1].

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| ζ_{SWG} | [kW] | Power losses of the SWG. |
| Eff_{SWG} | [%] | Efficiency of the SWG. |
| I | [A] | Current to load side of the SWG |
| I_{No} | [A] | Nominal current of the SWG. |
| LF | [-] | Load factor of the SWG. |
| P_{in} | [kW] | Power from grid side of the SWG. |
| P_{OIN} | [kW] | Power losses at nominal current. |
| P_{out} | [kW] | Power to load side of the SWG. |
| U_{out} | [V] | Output voltage. |

MATHEMATICAL DESCRIPTION

Norm IEC 60439-1 [2] and IEC 60947-2 [3] are references for circuit breaker designs. According to [1], the power losses of withdraw able circuit-breakers are

higher than those of the no load ones. Thus, this model considers only the losses generated by circuit-breakers, also called power losses at nominal current (P_{OIN}), and neglects the losses generated in busbars and wires. These power losses at nominal current grow quadratically with the load factor of the component. The load factor (LF), equation (2), determines at which capacity or state of charge the SWG is, it means, the percentage that the current to load side of the SWG (I), equation (1), represents compared to the nominal power of the SWG (I_{NO}). Moreover the power losses of the circuit-breakers equipped with thermomagnetic releases are higher than those of the circuit-breakers with electronic release.

Finally, using the following five equations one can compute the desired outputs of the component.

Current to load side of the SWG:

$$I = \frac{P_{out}}{U_{out} \cdot \sqrt{3}} \quad [A] \quad (1)$$

Load factor of the SWG:

$$LF = \frac{I}{I_{NO}} \quad [-] \quad (2)$$

Power losses of the SWG:

$$\zeta_{SWG} = P_{OIN} \cdot LF^2 \quad [kW] \quad (3)$$

Power from grid side of the SWG:

$$P_{in} = P_{out} + \zeta_{SWG} \quad [kW] \quad (4)$$

Efficiency of the SWG:

$$E_{ff} = \left(\frac{P_{out}}{P_{in}} \right) \cdot 100 \quad [\%] \quad (5)$$

ADDITIONAL INFORMATION

Different values for SWG parameters are given, classified by SWG type and load size. These parameters have been collected from a catalogue of a SWG manufacturer [1].

Table 9 Coefficients values for different types of SWG [1].

| SWG type | Load [kW] | P_{OIN} [kW] | I_{NO} [A] | U_{out} [V] |
|-----------------------|------------------|----------------|--------------|---------------|
| THERMOMAGNETIC | SWG1: 0<L>39 | 0.0153 | 55.7 | 400 |
| | SWG2: 39<L>193 | 0.0408 | 278.4 | 400 |
| | SWG3: 193<L>643 | 0.102 | 927.9 | 400 |
| | SWG4: 643<L>3214 | 0.360 | 4639.4 | 400 |
| ELECTRONIC | SWG1: 0<L>39 | 0.012 | 55.7 | 400 |
| | SWG2: 39<L>193 | 0.0318 | 278.4 | 400 |
| | SWG3: 193<L>643 | 0.090 | 927.9 | 400 |
| | SWG4: 643<L>3214 | - | - | - |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the SWG (kW)

Power send to the load connected at the SWG. This amount of power cannot give a current that exceeds the nominal current of the component.

Outputs are described below:

- Power losses of the SWG (kW)

Electrical losses associated with the circuit-breakers of the SWG.

- Power from grid side of the SWG (kW)

Power feed to the SWG in order to satisfy the load demand. This amount of power cannot give a current that exceeds the nominal current of the component.

- Load factor of the SWG (-)

This value defines at which percentage of the total capacity the SWG is working, 1 means that the component is working at its full

capacity. For physical sense, this value cannot be lower than 0 and greater than 1.

- Efficiency of the SWG (%)

Efficiency value of the component.

Parameters are described below:

- Power losses at nominal current (W)

Power losses at nominal current define the losses when the switchgear is operating at its maximum capacity current.

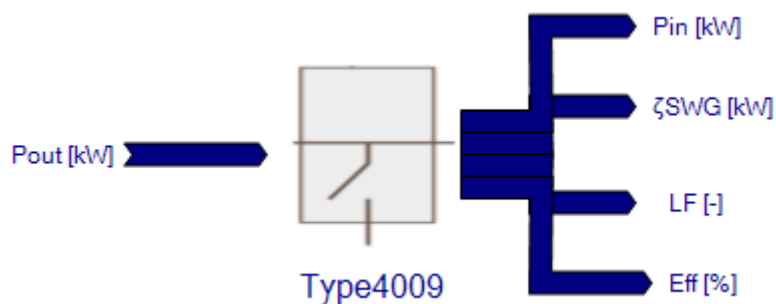
The power losses at nominal current can be found in the technical description of a SWG in an electrical catalogue.

- Nominal current of the SWG (A)

The nominal current of the switchgear defines the maximum current that can flow through the SWG. The power losses at nominal current must be specified for the selected SWG nominal current.

- Output voltage (V)

Distribution voltage.



Graphic 12 Scheme of type 4009

REFERENCES

- [1] ABB Circuit-breakers inside LV switchboards. ABB.
[http://www05.abb.com/global/scot/scot209.nsf/veritydisplay/40a2505a059a1f0e48257a700024aa1d/\\$file/1sdc007103g0202.pdf](http://www05.abb.com/global/scot/scot209.nsf/veritydisplay/40a2505a059a1f0e48257a700024aa1d/$file/1sdc007103g0202.pdf)
- [2] International Standard, IEC 60439-1, Low voltage switchgear and controlgear assemblies, Part 1: Type-tested (TTA) and partially type-tested assemblies (PTTA), 2001.
- [3] International Standard, IEC 60947-1, Low cvoltage switchgear and controlgear assemblies, Part 1: General rules, March, 2004.

7. STANDBY LOSSES OF A GENERATOR

7.1 TYPE 4005. STANDBY GENERATOR BASED ON REFERENCE POWER

Generator (from now GE) is a device that converts mechanical energy to electrical energy. Depending on the size and the final use of generator, this device could be used as the primary energy source of the system or as a backup energy source in case of a failure from the main energy source. Usually these devices spend most of their operational time in a standby mode, generating power losses, while are waiting to start to supply power.

Type 4005 is a simplified model to approximate the standby losses of a GE. The model use a mathematical equation, based on empirical coefficients, to quantify the standby losses. These losses are assumed constant during the simulation time. As an example, a value for the coefficients can be found in the tool provided by Schneider [1].

NOMENCLATURE

| | | |
|--------------|------|-----------------------------|
| C_F | [–] | No load losses coefficient. |
| C_S | [–] | Sizing coefficient. |
| ζ_{GE} | [kW] | Standby losses of the GE. |
| P_N | [kW] | Nominal power of the GE. |
| P_{Ref} | [kW] | Reference power. |

MATHEMATICAL DESCRIPTION

This component computes the electrical losses of a standby GE (ζ_{GE}), based on the nominal power (P_N) and the no load losses coefficient (C_F). The type calculates the nominal power of the GE multiplying the sizing coefficient (C_S) by

the reference power of the system (P_{Ref}), equation (1). The standby losses are approximated multiplying the no load losses coefficient by the nominal power of the GE, equation (2). The no load losses are going to be constant during the simulation time because are independent of the load. These losses are attributable to powering such things as; transformers, logic boards or communication cards.

Therefore, the model considers the two equations below to calculate the standby losses of the GE.

Nominal power of the GE:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Standby losses of the GE:

$$\zeta_{GE} = P_N \cdot C_F \quad [kW] \quad (2)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above in Table 1, which is valid for Data Centre according to [1]. If the GE is installed into a Data Centre, the total installed power (IT + cooling) must be taken as the reference power.

Table 10 Coefficients for standby losses of a Generator [1].

| System | C_S | C_F |
|------------------|-------|-------|
| Generator | 2.5 | 0.003 |

INPUTS, OUTPUTS AND PARAMETERS

Outputs are described below:

- Standby losses of the GE (*kW*)

Generator losses at 0% load, associated with the standby mode.

Parameters are described below:

- Sizing coefficient (-)

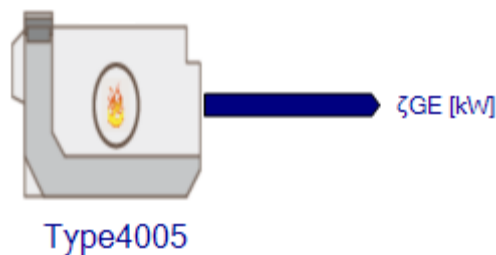
This coefficient is used to approximate the nominal power of the component. The nominal power is computed multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- No load losses coefficient (-)

Describes the standby losses as a percentage of the nominal power of the GE.

- Reference power (kW)

The reference power is the installed power of our system. If the GE is installed into a Data Centre, the total installed power (IT + cooling) must be taken as the reference power.



Graphic 13 Scheme of type 4005

REFERENCE

[1] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

8. LIGHTING CONSUMPTION (LGT)

8.1 TYPE 4006. LGT BASED ON REFERENCE POWER .

Numerous lighting devices are available nowadays in the market, where the trend of these devices is to ensure the same lighting conditions while energy consumption is reduced. Proper lighting can enhance task performance, improve the appearance of an area, or have positive psychological effects on occupants.

Type 4006 is a simplified model to approximate the lighting consumption. The model use a mathematical equation, based on an empirical coefficient, to quantify the power consumption of lightning. This consumption is assumed constant during the simulation time. As an example, values for the coefficients can be found in the tool provided by Schneider [1].

NOMENCLATURE

| | | |
|-----------|------|---------------------------------|
| C_L | [-] | Load coefficient. |
| C_S | [-] | Sizing coefficient. |
| P_{in} | [kW] | Power consumption of the LGT. |
| P_N | [kW] | Total nominal power of the LGT. |
| P_{Ref} | [kW] | Reference power. |

MATHEMATICAL DESCRIPTION

This component computes the electrical consumption associated to LGT (P_{in}) based on the reference power of our system (P_{Ref}) and the load coefficient (C_L).

The type approximates the “total nominal power” (P_N) of the LGT devices installed in our system, multiplying the sizing coefficient (C_S) by the reference power, equation (1). Notice that if the sizing coefficient is used with the default value, the “total nominal power” of LGT is equal to the reference power of our installation.

The consumption is then calculated as a percentage of this “total nominal power” using the load coefficient, as is shown in equation (2). This consumption is assumed constant during the simulation time.

Therefore, the model considers the two equations below to calculate the electrical consumption of lighting devices.

Total nominal power of the LGT:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Power consumption of the LGT:

$$P_{in} = P_N \cdot C_L \quad [kW] \quad (2)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for Data Centre according to [1]. If the LGT are installed into a Data Centre the installed IT power must be taken as the reference power.

Table 11 Coefficients for the LGT [1]

| System | C_S | C_L |
|-----------------|-------|-------|
| Lighting | 1.0 | 0.010 |

INPUTS, OUTPUTS AND PARAMETERS

Outputs are described below:

- Power consumption of the LGT (*kW*)

Power demanded by LGT devices.

Parameters are described below:

- Sizing coefficient (-)

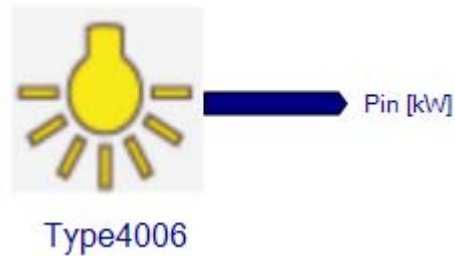
This coefficient is used to approximate the “total nominal power of the LGT” The total nominal power is computed multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- Load coefficient (-)

Describes the power consumption of LGT as a percentage of the “total nominal power of the LGT”.

- Reference power (kW)

The reference power is the installed power of our system. If the LGT is installed into a Data Centre, the installed IT power must be taken as the reference power.



Graphic 14 Scheme of type 4006

REFERENCE

[1] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

8.2 TYPE 4013. LGT BASED ON AREA

Numerous lighting devices are available nowadays in the market, where the trend of these devices is to ensure the same lighting conditions while energy consumption is reduced. Proper lighting can enhance task performance, improve the appearance of an area, or have positive psychological effects on occupants.

Type 4013 is a simplified model for lighting. The model use a mathematical relation, based on a constant coefficient, which defines an amount of power consumption per square meter. Ham, S. et al [1], specifies a value of 10 W/m² for the white space of Data Centre. However, this value can be approximated dividing the number of watts, of lighting installed, by the squares meters to be illuminated.

NOMENCLATURE

| | | |
|-------------|---------------------|------------------------------------------------------------|
| P_{LGT} | [kW] | Power consumption of LGT. |
| t_{delay} | [min] | Time delay of the LGT. |
| A_{room} | [m ²] | Area of the room to be illuminated. |
| CS | [–] | ON/OFF control signal. |
| C_t | [–] | Time ratio between LGT time delay and simulation timestep. |
| CO_{LGT} | [W/m ²] | Consumption coefficient of LGT. |
| Δt | [hr] | Simulation time step. |

MATHEMATICAL DESCRIPTION

The power consumption of lighting devices (P_{LGT}) can be approximated using a relation between the square meters to be illuminated (A_{room}) and the power consumption coefficient per square meter (CO_{LGT}). In order to do that, the type asks the user to enter the square meters to be illuminated and the consumption

coefficient per square meter. Thus, using equation (1), the type computes the electrical consumption associated to lighting devices.

Power consumption of LGT:

$$P_{LGT} = \frac{CO_{LGT} \cdot A_{room}}{1000} \quad [kW] \quad (1)$$

In order to approximate the operationally of advanced lighting devices, the types also includes an input called control signal (CS) and a parameter value called time delay (t_{delay}). The input value, control signal, is used in order to take into account the fact that the lighting devices can be controlled by a sensor, which keeps the lights on if someone is inside the room, control signal equal to 1, and turns it off if the room is empty, control signal equal 0. Moreover, as these devices have some time delay after switch off, in order to avoid be switching between on and off mode if someone keeps entering and leaving from the room, the type includes the parameter time delay which will keep the light on for some minutes after the control signal becomes zero. Notice that if the time delay is smaller than the simulation time step (Δt) the type will be not able to reproduce the delayment after switch off.

Being;

$$C_t = \frac{t_{delay}}{60 \Delta t}$$

If $CS > 0$:

$$P_{LGT} = \frac{CO_{LGT} \cdot A_{room}}{1000}$$

Else if $C_t < 1$ & $CS < 0$:

$$P_{LGT} = \frac{CO_{LGT} \cdot A_{room}}{1000}$$

Just happen, the time step after occupancy becomes zero.

Else $C_t \geq 1$ & $CS < 0$:

$$P_{LGT} = \frac{CO_{LGT} \cdot A_{room}}{1000}$$

Just happen, the time step after occupancy becomes zero. A counter will ensure that the lightning keeps on a number of time steps equal to C_t .

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- ON/OFF Control signal (-)

Control signal keeping the lights turned on (=1) or off (=0).

Outputs are described below:

- Power consumption the LGT(kW)

Power consumption of lighting devices.

Parameters are described below:

- Time delay (min)

Time delay after switch off the lights, notice that if this value is smaller than the simulation time step the type won't be able to extend the power consumption.

- Illuminated area (m2)

Area of the room to be illuminated.

- Consumption coefficient of the LGT (W/m2)

Describe the power consumption per square meter associated to the lighting devices.



Graphic 15 Scheme of type 4013

REFERENCES

- [1] S. W. Ham, M. H. Kim, B. N. Choi, J. W. Jeong, Simplified server model to simulate data center cooling. *Energy and Buildings*, 86, 2015, 328-339.

9. MISCELLANEOUS CONSUMPTIONS (MISC)

9.1 TYPE 4007. MISC BASED ON REFERENCE POWER.

Miscellaneous consumption is defined as the diverse consumptions of many devices (usually low consumptions) that are part of a system but that do not define it. Type 4007 is a simplified model to consider auxiliary or miscellaneous (from now MISC) electrical consumptions. The model uses a mathematical equation, based on an empirical coefficient, to describe the electrical consumption of auxiliary devices such as emergency lights or small fans and pumps. This consumption is going to be assumed constant during the simulation time. As an example, values for the coefficients can be found in the tool provided by Schneider [1].

NOMENCLATURE

| | | |
|-----------|------|----------------------------------|
| C_L | [–] | Load coefficient. |
| C_S | [–] | Sizing coefficient. |
| P_{in} | [kW] | Power consumption of the MISC. |
| P_N | [kW] | Total nominal power of the MISC. |
| P_{Ref} | [kW] | Reference power. |

MATHEMATICAL DESCRIPTION

This component computes the electrical consumption of auxiliary devices (P_{in}), based on the reference power of our system (P_{Ref}) and the load coefficients (C_L).

The type approximates the “total nominal power” of the MISC devices installed in our system (P_N), multiplying the sizing coefficient (C_S) by the reference power (P_{Ref}), equation (1). Notice that if the sizing coefficient is used with the default value, the “total nominal power” of MISC is equal to the reference power of our installation. The consumption is then calculated as a percentage of this “total nominal power” using the load coefficient, as is shown in equation (2). This consumption is assumed constant during the simulation time.

Therefore, the model considers the two equations below to calculate the electrical consumption of MISC devices.

Total nominal power of the MISC:

$$P_N = P_{Ref} \cdot C_S \quad [kW] \quad (1)$$

Power consumption of the MISC:

$$P_{in} = P_N \cdot C_L \quad [kW] \quad (2)$$

ADDITIONAL INFORMATION

As an example, a set of values for the coefficients defined above are in Table 1, which are valid for Data Centre according to [1]. If the MISC are installed into a Data Centre the installed IT power must be taken as the reference power.

Table 12 Coefficients for Miscellaneous [1].

| System | C_S | C_L |
|----------------------|-------|-------|
| Miscellaneous | 1.0 | 0.016 |

INPUTS, OUTPUTS AND PARAMETERS

Outputs are described below:

- Power consumption of the MISC (*kW*)

Power demanded by MISC devices.

Parameters are described below:

- Sizing coefficient (-)

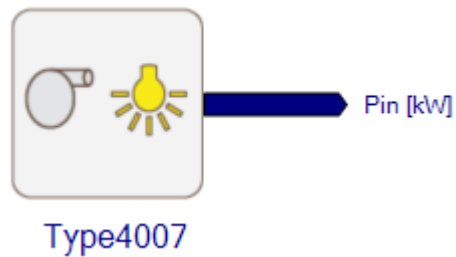
This coefficient is used to approximate the total nominal power of the MISC devices. The total nominal power is computed multiplying the sizing coefficient by the reference power. The reference power defines the installed power of our system.

- Load coefficient (-)

Describes the power consumption of MISC equipment as a percentage of the “total nominal power” of the MISC devices.

- Reference power (*kW*)

The reference power is the installed power of our system. If the MISC are installed into a Data Centre, the installed IT power must be taken as the reference power.



Graphic 16 Scheme of type 4007

REFERENCE

[1] Schneider Electric, APC tool (2014) Data Centre Efficiency Calculator, Assumptions. http://www.apcmedia.com/salestools/WTOL-7CMGPL/WTOL-7CMGPL_R3_EN.swf

10. TRANSFORMER (TR)

10.1 TYPE 4008. TRANSFORMER BASED ON MANUFACTURER PROPERTIES

A transformer is an electrical device that transfers energy between two or more circuits through electromagnetic induction. A wide range of transformer designs have been developed for electronic and electric power applications.

Type 4008 is a mathematical model for a transformer unit (TR). The model use a mathematical equation, based on empirical coefficients, to describe the operational losses of a TR system. These coefficients summarize the main effects that contribute to the operational losses of a TR unit. These set of coefficients can be find in catalogues provided by transformer manufacturers, such as in [3] and [4].

NOMENCLATURE

| | | |
|--------------|------|---------------------------------|
| ζ_{TR} | [kW] | Power losses of the TR. |
| Eff_{TR} | [%] | Efficiency of the TR. |
| LF | [-] | Load factor of the TR. |
| P_0 | [W] | No Load losses coefficient. |
| P_{in} | [kW] | Power from grid side of the TR. |
| P_K | [W] | Load losses coefficient. |
| P_N | [kW] | Nominal power of the TR. |
| P_{out} | [kW] | Power to load side of the TR. |

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to a transformer (ζ_{TR}). For energy efficiency calculation, it is necessary to know short-circuit voltage (%) and angle ($\cos(\pi)$), and these variables are quite difficult to find. Accordingly,

power losses for the transformer are to be characterized applying the new "Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers", N° 548/2014 [1]. According to [1] and [2], power transformers <3.15 kVA and Um < 36 kV, has to respect maximum losses as defined in EN 50464-1:2007 and EN 50541-1:2011. These documents are being modified in order to be consistent between them. The formulae for energy efficiency according to EN 50541-1:2011 can be found in [3].

It is well known, that the losses in transformers are generated mainly by three phenomena: hysteresis, eddy currents and joule losses. The first two phenomena are constantly present in the functionality of the transformer; the last one gains presence when the load factor (LF) of the transformer increases. The load factor determines at which capacity or state of charge the TR is, it means the percentage that power to the load side of the TR (P_{out}) represents compared to the nominal power of the TR (P_N). The no load losses coefficient (P_0), summarize the contribution by hysteresis and eddy's current phenomena. More over the load loss coefficient (P_K) represents the joule losses through transformer wires.

Using the following four equations, the calculation of the desired outputs can be performed:

Load factor of the TR:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (1)$$

Power losses of the TR:

$$\zeta_{TR} = P_0 + P_K \cdot LF^2 \quad [kW] \quad (2)$$

Power from grid side of the TR:

$$P_{in} = P_{out} + \zeta_{TR} \quad [kW] \quad (3)$$

Efficiency of the TR:

$$Eff_{TR} = \frac{LF \cdot P_N}{LF \cdot P_N + P_0 + P_K \cdot LF^2} \cdot 100 \quad [\%] \quad (4)$$

ADDITIONAL INFORMATION

Different values for transformer parameters are in Table 1, classified by transformer type and load size. These parameters have been extracted from manufacturers [3] and [4].

Table 13 Coefficient values for different types of TR [3] and [4]

| TR type | Load [kW] | P_N [kVA] | P_0 [kW] | P_K [kW] |
|------------------------|-------------------------|----------------|------------|------------|
| ECO- DESIGN | <u>TR1</u> : 0<L>39 | 50 | 0.18 | 1.5 |
| | <u>TR2</u> : 39<L>193 | 250 | 0.32 | 3.9 |
| | <u>TR3</u> : 193<L>643 | 800 | 0.57 | 7.64 |
| | <u>TR4</u> : 643<L>3214 | 4200 | 2.1 | 31 |
| COMMON | <u>TR1</u> : 0<L>39 | 50 | 0.35 | 1.5 |
| | <u>TR2</u> : 39<L>193 | 250 | 0.88 | 3.8 |
| | <u>TR3</u> : 193<L>643 | 800 | 2.1 | 9.4 |
| | <u>TR4</u> : 643<L>3214 | 4000 | 5.5 | 33 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the TR (*kW*)

Power send to the load connected at the TR. This amount of power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the TR (*kW*)

Electrical losses associated with the operability of the component.

- Power from grid side of the TR (kW)

Power feed to the TR in order to satisfy the load demand. The input power cannot exceed the nominal power of the component.

- Load factor of the TR (-)

This value defines the percentage of the total capacity at which the TR is working. A load factor of 1 means that the component is working at its full capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the TR (%)

Efficiency value of the component.

Parameters are described below:

- No-Load losses coefficient (kW)

No-load losses are the losses at 0% load. These losses are caused by the alternating magnetization of the core (hysteresis loss) and by eddy-currents in the core, they occur as soon as a transformer is energized.

The no-load losses parameters can be found in the technical descriptions of a TR in an electrical catalogue.

- Load losses coefficient (kW)

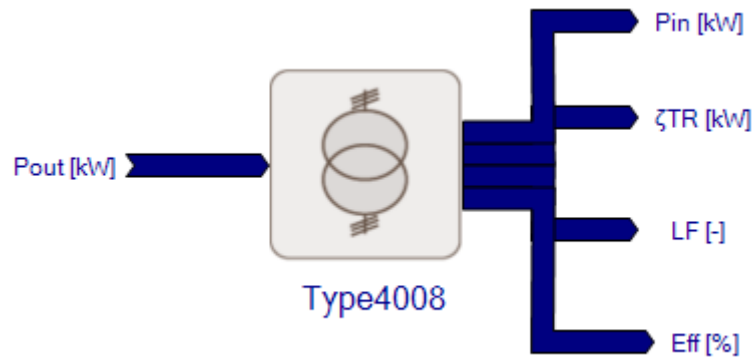
Load losses are caused by losses in the conductors (resistive and eddy current) they have a quadratic dependence on the load factor.

The load losses parameters can be found in the technical descriptions of a TR in an electrical catalogue.

- Nominal power of the TR (kW)

The nominal power of a transformer defines the maximum power that can flow through the component.

Nominal power of transformer can be found in the TR characteristics descriptions in an electrical catalogue



Graphic 17 Scheme of type 4008

REFERENCE

[1] COMMISSION REGULATION (EU) No 548/2014. Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers. Available online: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2014:152:FULL&from=EN>

[2] ABB Transformadores energéticamente eficientes. Reglamento europeo de rendimiento energético mínimo (MEPS). Available online: [http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/33dc0a9fdb993170c1257d9300283bd2/\\$file/Energy%20efficient%20transformer%20solution_1LAB000572_sp_1st%20edition.pdf](http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/33dc0a9fdb993170c1257d9300283bd2/$file/Energy%20efficient%20transformer%20solution_1LAB000572_sp_1st%20edition.pdf)

[3] Technical data EcoDry dry-type transformers. ABB. Available online: [http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/b1255490e21b02cb c1257b6b0049d534/\\$file/1LDE000122%20en%20data%20sheet%20EcoDry%20transformers.pdf](http://www05.abb.com/global/scot/scot252.nsf/veritydisplay/b1255490e21b02cb c1257b6b0049d534/$file/1LDE000122%20en%20data%20sheet%20EcoDry%20transformers.pdf)

[4] ABB catalogue. Vacuum cast coil dry type distribution transformers. Available online: [http://www04.abb.com/global/seitp/seitp202.nsf/0/1a97c23d16c6212ec1257673004c67ca/\\$file/Vacuum+cast+coil+dry+type+distribution+transformers.pdf](http://www04.abb.com/global/seitp/seitp202.nsf/0/1a97c23d16c6212ec1257673004c67ca/$file/Vacuum+cast+coil+dry+type+distribution+transformers.pdf)

11. POWER SUPPLY UNIT (PSU)

11.1 TYPE 4012. PSU BASED ON MANUFACTURER PROPERTIES

Power supply unit (from now PSU) is a device in charge of supply properly the power to the servers; correcting voltage disturbances and avoiding exceed current capacities. Moreover, can provide energy to the IT equipment during milliseconds allowing switches to actuate and avoid power shutdowns.

Type 4012 is an empirical model for a PSU. The model uses a mathematical equation, based on empirical coefficients, to describe the operational losses of a PSU. If the efficiency curve of the PSU is known, the coefficients can be deduced following the data regression technique described by Avelar, V. et al [1]. Usually manufacturers do not provide the entire efficiency curve of a PSU, but this can be deduced, for some companies, with the data available in 80 plus website [2]. 80 Plus is a proposed test protocol, which uses existing industry standards that have been created for electronic test and measurement, to develop a consistent and repeatable method for measuring the energy efficiency of PSU.

NOMENCLATURE

| | | |
|---------------|------|----------------------------------|
| C_F | [kW] | No load losses coefficient. |
| C_P | [kW] | Proportional losses coefficient. |
| C_Q | [kW] | Square – law losses coefficient. |
| ζ_{PSU} | [kW] | Power losses of the PSU. |
| LF | [–] | Load factor of the PSU. |
| N | [–] | Number of PSU in parallel. |
| P_{in} | [kW] | Power from grid side of the PSU. |
| P_N | [kW] | Nominal power of the PSU. |

P_{out} [kW] Power to load side of the PSU.

MATHEMATICAL DESCRIPTION

This component computes the electrical losses associated to a PSU (ζ_{PSU}) based on the load factor (LF) and three losses coefficients (C_F , C_P and C_Q).

The load factor is the percentage between the power to the load side of the PSU (P_{out}) and to the nominal power of the PSU (P_N), equation (1). The losses coefficients can be obtained from the efficiency curve, if it's provided by manufacturers. If the efficiency curve it's not know this can be deduced, for some manufacturers, with the data available in the 80 Plus website [2]. The 80 Plus performance specification requires multi-output power supplies in computer and servers to be 80% or greater efficient at 20%, 50% and 100% of the nominal power. The efficiency curve allows us to know the losses at different load factor, plotting these losses and applying a data regression, as is shown in Avelar, V. et al [1], and equation, describing the losses, can be obtained, equation (2). As can be appreciated, this equation depends on the load factor and three coefficients. These coefficients are:

- No load losses coefficient (C_F): describes the PSU standby losses, PSU losses at 0% load, attributable to powering such things as logic boards and communication cards. These losses are independent of the load.
- Proportional losses coefficient (C_P): As more power is added to the PSU, a larger amount of power will be flowing by various components in its power path, thus losses will increase. This coefficient, describes the losses that grow linearly with the load factor.
- Square-law losses coefficient (C_Q): As more power is added to the PSU, more current flows through its components. This causes losses in the PSU with the square of the current. This coefficient, describes the losses that grows quadratically with the load factor.

Internally the type divides the power to load side of the PSU by the number of PSU in parallel (N). At the end of the time step, in order to know the total power

from grid side of the PSU (P_{in}), the type multiplies the power to load side and the power losses of the PSU by the number of PSU in parallel.

Therefore, the model considers the four following equations to compute the electrical losses of a PSU component.

Load factor of the PSU:

$$LF = \frac{P_{out}}{P_N} \quad [-] \quad (1)$$

Power losses of the PSU:

$$\zeta_{PSU} = (C_F + C_P \cdot LF + C_Q \cdot LF^2) \quad [kW] \quad (2)$$

Power from the grid side of the PSU:

$$P_{in} = P_{out} + \zeta_{PSU} \quad [kW] \quad (3)$$

Efficiency of the PSU:

$$E_{ff} = \left(\frac{P_{out}}{P_{in}} \right) \cdot 100 \quad [\%] \quad (4)$$

ADDITIONAL INFORMATION

Different values for the PSU parameters are in Table 1, classified by PSU category and model, for a determined manufacturer [3]. These parameters have been deduced with the information extracted from the 80 Plus website [2].

Table 14 Coefficients values for different types of PSU [2] and [3].

| PSU manufacturer | PSU model | Category | P_N [kW] | C_F [kW] | C_P [kW] | C_Q [kW] |
|----------------------------|-----------|----------|------------|------------|------------|------------|
| <u>3Y Power Technology</u> | YM-2721A | Bronze | 0.734 | 0.02100 | 0.02910 | 0.03350 |
| | YM-2721B | Silver | 0.727 | 0.0189 | 0.0248 | 0.0443 |
| | YM-2721C | Gold | 0.728 | 0.0132 | 0.0096 | 0.0498 |
| | YM-681HG | Platinum | 0.702 | 0.0069 | 0.0104 | 0.0368 |

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Power to load side of the PSU (kW)

Power send to the load connected at the PDU. This amount of power cannot exceed the nominal power of the component.

Outputs are described below:

- Power losses of the PSU (kW)

Electrical losses associated with the operability of the component.

- Power from the grid side of the PSU (kW)

Power feed to the PSU in order to satisfy the load demand. This power cannot exceed the nominal power of the component.

- Load factor of the PSU (-)

This value defines the percentage of the total capacity at which the PSU is working, 1 means that the component is working at its full

capacity. For physical sense, this value cannot be lower than 0 or greater than 1.

- Efficiency of the PSU (%)

Efficiency value of the component.

Parameters are described below:

- No load losses coefficient (kW)

Describes the PSU standby losses.

- Proportional losses coefficient (kW)

Describes the PSU losses that grow linearly with the load factor.

- Square-law losses coefficient (kW)

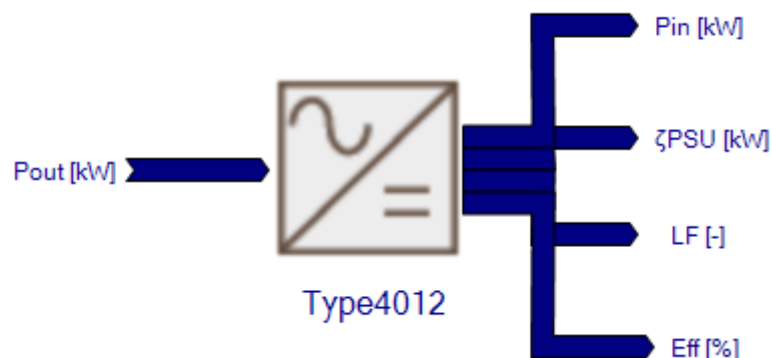
Describes the PDU losses that grow quadratically with the load factor.

- Nominal power of the PSU (kW)

The nominal power of defines the maximum power that can flow through the component.

- Number of PSU in parallel (-)

Number of PSU installed in parallel.



Graphic 18 Scheme of type 4012

REFERENCES

- [1] Avelar, V. Making Large UPS Systems More Efficient, White paper #108, APC, Schneider, 2007.
- [2] Data from Plug Load Solutions, website:
<http://www.plugloadsolutions.com/80PlusPowerSupplies.aspx>
- [3] 3Y Power Technology, website: <http://www.3ypower.com/?p=3&lang=2&s=1>

12. WAVE ENERGY CONVERTER (WEC)

12.1 TYPE 4014. WEC

Wave energy has been recognized by the international community as a renewable energy source with a huge potential to contribute into the electricity market. The ocean energy is a predictable and abundant source, these properties makes it interesting to analyse and characterize for further investments on this area.

Type 4014 is a simplified model for analyse the potential wave energy in a certain location. The wave energy is approximated by the main wave height and period, using the formula developed by D. Vicinanza et al [1]. Moreover, the type approximates the power generation based on the capture length value of the WEC (Wave Energy Converter) system. The WEC systems available are: Wave Dragon, AquabuOY and Pelamis.

NOMENCLATURE

| | | |
|----------------|---------------------------------------------|----------------------------------|
| T_s | [s] | Peak wave period. |
| H_m | [m] | Wave height. |
| ρ_{water} | $\left[\frac{\text{kg}}{\text{m}^3}\right]$ | Sea water density. |
| α | [–] | Spectrum correction coefficient. |
| T_E | [s] | Wave energy period. |
| g | $\left[\frac{\text{m}}{\text{s}^2}\right]$ | Gravity. |
| P_{wave} | $\left[\frac{W}{m}\right]$ | Wave energy. |
| N | [–] | Number of WEC units. |
| P_{gen} | [kW] | Generated power. |
| CL_{WEC} | [m] | Capture length of WEC system. |

MATHEMATICAL DESCRIPTION

The model approximates the wave energy power (P_{wave}) of a certain location, using the wave height (H_m) and approximating the wave energy period (T_E), as is specified in D. Vicinanza et al [1]. The energy period is rarely specified and must be estimated from other variables when the spectral shape is unknown. One approach, when the wave peak period (T_s) is known, is to use equation (1). The peak wave period is the inverse of the frequency at which the wave spectrum has its highest energy density, and is also referred to as the dominant wave period. This value is necessary for formulating the theoretical spectrum. The spectrum correction coefficient (α) depends on the shape of the wave spectrum, when the spectrum correction coefficient increases the spectral width decreases. Different approaches to the spectrum correction coefficient value are available in literature, as in Pastor, J. et al [2], where the more conservative assumption is set $\alpha = 0.9$, which is equivalent to assume a standard JONSWAP spectrum with a peak enhancement factor of 3.3. Finally, the generated power (P_{gen}) is approximated using the capture length (CL_{WEC}) of our WEC system and the number of units installed (N). The capture length depends on the type of WEC used and is internally approximated by the type using a set of correlations. These correlations define the capture length, for each wave height and all the profitable wave periods by the WEC, relating the performance map provided by manufactures [3] and the wave power potential approximated by equation (2). Therefore the wave energy in deep water, can be roughly approximated, with the wave height and the peak wave period as input data and the three following equations.

Energy period:

$$T_E = \alpha \cdot T_s \quad [s] \quad (1)$$

Wave energy power:

$$P_{wave} = \frac{\rho_{water} \cdot g^2 \cdot H_m^2 \cdot T_E}{64 \cdot \pi} \quad \left[\frac{kW}{m} \right] \quad (2)$$

WEC generated power:

$$P_{gen} = (P_{wave} \cdot CL_{WEC}) \cdot N_{units} \quad [kW] \quad (3)$$

Where CL WEC depends on H_m and T_g

INPUTS, OUTPUTS AND PARAMETERS

Inputs are described below:

- Peak wave period (s)

Peak wave period of the location to be analysed. Input used to measure the incident energy of the sea state.

- Wave height (m)

Wave height of the location to be analysed. Input used to measure the incident energy of the sea state.

Outputs are described below:

- Wave power (kW/m)

Potential power of the incident wave.

- Generated power (kW)

Power generated by the WEC system from the incident wave.

Parameters are described below:

- Sea water density (kg/m^3)

Density of the sea water. As a default value $1027kg/m^3$ is used, considering an average water salinity concentration of 33ppm and an average water temperature of $7^\circ C$.

- Period correction coefficient (-)

Value used to derive the wave energy period from the peak wave period when the spectrum shape is unknown. As a default value 0.9 is used, which is equivalent to assumed a standard JONSWAP spectrum with a peak enhancement factor of 3.3

- Type of WEC (-)

Wave energy converter system used. (Wave Dragon =1, AquabuOY=2 and Pelamis=3).

- Number of WEC units (-)

Number of WEC units installed to generated power.



REFERENCE

[1] D. Vicinanza, P. Contestabile and V. Ferrante, “Wave energy potential in the north-west of Sardinia”, *Renewable Energy (ELSEVIER)*, vol. 50, pp. 506-521, 2013.

[2] J. Pastor, Y. Liu, Y. Dou, “Wave Energy Resource Analysis for use in Wave Energy Conversion”, *Proceedings of the Thirty-Sixth Industrial Energy Technology Conference*, New Orleans, LA. May 2014.

[3] Dunnett, D. Wallace, J.S. “Electricity generation from wave power in Canada”, *Renewable Energy (ELSEVIER)*, vol. 34, pp. 179-195, 2009.