Simulation of Autonomous Electrical Power Systems

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Contents

1 INTRODUCTION

This document is dealing with the software to simulate an electrical power system, where solar and wind act as power producers. The basic principle is based on a statistical processing of incoming solar radiation towards the solar generators, wind speed against wind generators, and load power from electricity consumers. The main purpose of the current software, is to enable quantitative dimensioning of the key components of an autonomous system. The software is also adapted for connection of the autonomous system to an external power grid. One advantage of such an arrangement is of course a reduced need for back-up generators (eg diesel generator). Although any surplus energy, can in such a case, in a simple way be exported. The current software has been developed to offer the possibility of prediction of actual solar energy with time of day, season and geographical location as input parameters.

Fig. 1 shows the main components in an autonomous power system with wind and solar as power producers.

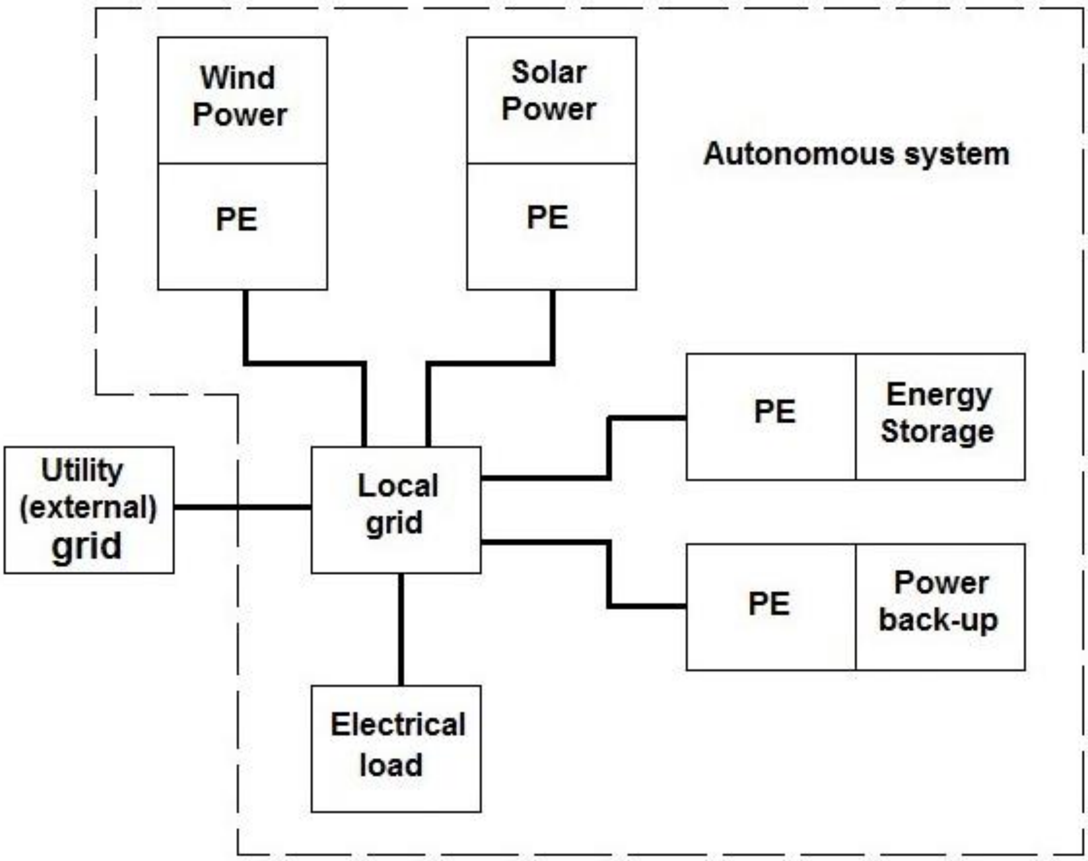

Fig. 1. The main components in an autonomous power system with wind and solar as power producers.

Subsystems in an autonomous power system with wind and solar as power producers according to Fig. 1:

Wind Power: Wind power plant.
Solar Power: Solar power plant.
Local grid: autonomous power grid.
Utility grid: power grid with facility to handle situations of energy deficit and energy surplus.
Energy storage: storage device with two purposes: 1) To store surplus energy. 2) To supply energy to the local grid to meet an energy deficit.
Power back-up: This can be e.g. a diesel generator.
Electrical load: Active and reactive local electrical load.
PE: power electronics for electrical adaptation.

2 SIMULATION SYSTEM

2.1 Overview

The simulation system is built up of 9 modules according to Table I. The intention of the system is to enable a statistical basis for evaluation of a power system.

Table I. The modules in the simulation system.

System Modules	Function
Wind_make	Stochastic wind speed
Wind_turbine	Electrical wind power
Extinction_make	Stochastic extinction coefficients
Sun_intensity	Solar irradiation
Sun_panel_generator	Electrical solar power
Load_make	Stochastic load
Connect_gen_load	See section 2.8
Storage_distribution	See section 2.9
Power_evaluate	Simulation evaluation

The simulation flowchart is illustrated in Fig. 2. The loop is repeated “N” times. Evaluation of the simulation is presented in the form of statistical parameters. To achieve statistical significance regarding the final result, “N” should be at least in the order of 100.

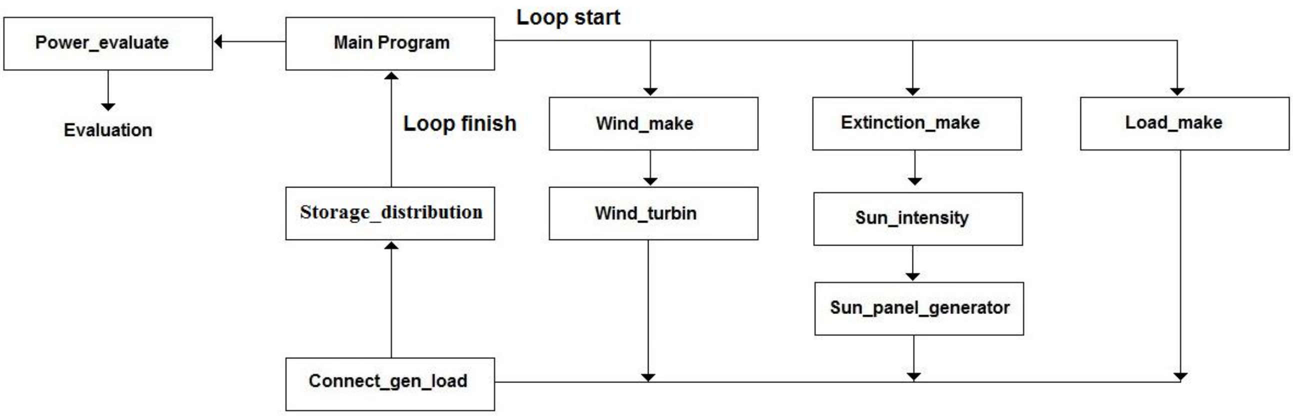

Fig. 2. Simulation flowchart. The loop repeated “N” times.

The modules are descripted in sections 2.2 to 2.10.

2.2 Module Wind_make

2.2.1 General description

The program module “Wind_make” generates stochastical wind speeds consisting of two components according to:

Equ. 1 $$V = V_B + V_N$$

Where: V: Total wind speed
V_B: Base component
V_N: Noise component

V_B is generated by a Weibull process
with the density function:

Equ. 2 $$W(A,C) = \frac{C}{A}\left(\frac{V_B}{A}\right)^{C-1} e^{-\left(\frac{V_B}{A}\right)^C}$$

Where: A,C: Weibull parameters

The base component is updated with equally spaced intervals during a simulation process. In order to get statistical confidence, this is done 10 times during a simulation process.

The component V_N is generated by using a factor C_W according to:

Equ. 3 $$V_N = V_B \times C_W$$

C_W is given by a Laplace distribution according to Equ. 4.

Equ. 4 $$p(x) = \frac{1}{2 \cdot \emptyset} \times \exp\left(- \frac{|x - \theta|}{\emptyset}\right)$$

The Laplace parameters have been chosen according to:

$\emptyset = 0.16$
$\theta = 0$

Updating of C_W is done each simulation step.

Fig. 3 illustrates the updating of V_B and V_N.

Fig. 3. The updating of V_B and V_N during a simulation process.

A detailed description of the statistical princip for wind generation is given in [1].

2.2.2 Examples

Fig. 4 shows an example of stochastical generated wind profile with Weibull parameter A = 6.2 and C = 1.9.

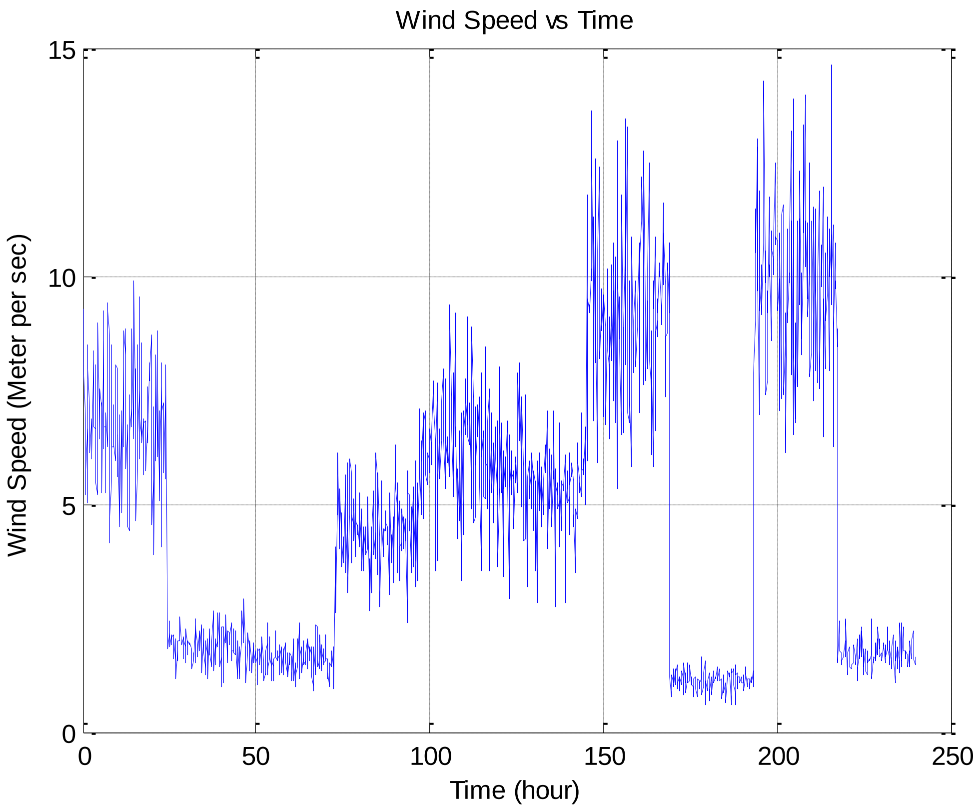

Fig. 4. Stochasticaly generated wind speed with Weibull parameter A = 6.2 and C = 1.9.

2.2.3 Input/Output parameters

Input parameters to the module:

- Weibullparameters A and C

Output parameters from the module:

- Stochastical wind speeds to module “Wind_turbine”.

2.3 Module Wind_turbine

2.3.1 General description

The program module "Wind_turbine" simulates the function of a wind farm consisting of one or more wind turbines. The active generated power is calculated according to:

Equu. 5 $$Pw = \frac{Cp \times \rho \times A \times V^3 \times Pfw \times Nt}{2}$$

Where:

Pw: Generated active wind power (W)
$C_p(\lambda)$: Power coefficient
ρ: Air density (kg/m^3)
A: Rotor sweeping area (m^2)
V: Wind speed (m/s)
Pfw: Wind power turbine efficiency excluding Cp
Nt: Number of wind power turbines in the farm
The air density (ρ) is calculated according to:

Equ. 6 $$\rho = \frac{1.293}{1+0.00367 \times Tair} \times \frac{Pair}{1013}$$

Where:

Tair: Air temperature (°C)
Pair: Air pressure (mbar)

The rotor sweeping area (A) is calculated according to:

Equ. 7 $$A = \pi \times \frac{D^2}{4}$$

Where: D: Rotor diameter

Power coefficient $C_p(\lambda)$ is in the module calculated according to:

Equ. 8 $$C_p(\lambda) = a0 + a1\lambda + a2\lambda^2 + a3\lambda^3 + a4\lambda^4 + a5\lambda^5$$

Where:

λ: Tip speed ratio
a0 = 1.142515

a1 = -1.253909
a2 = 4.78158×10^{-1}
a3 = -7.554×10^{-2}
a4 = 5.426×10^{-3}
a5 = -1.4623×10^{-4}

The tip speed ratio (λ) is calculated according to:

Equ. 9 $\lambda = Vt / V$

Where:

Vt: Wind turbine blade tip speed (m/s)
V: Wind speed (m/s)

The turbine rotor rotation speed is calculated according to:

Equ. 10 $$V_{rotor} = \frac{Vt}{\pi \times D} \times 60$$

Where: V_{rotor}: Turbine rotor rotation speed of the

The rotation speed is regulated to get the optimal value of tip speed ratio for the current wind speed. See Equ. 9. This value is unique for the wind turbine in question and means that $C_p(\lambda)$ is optimized. See Equ. 8 and thereby that Pw optimized. See Equ. 5.

If the wind speed exceeds a certain defined maximum level the turbine(s) is (are) stopped, resulting in no output power. If the wind speed is lower than a certain defined minimum level the turbine(s) does (do) not produce any output power.

Generated reactive power is a function of the "Phase Angle".

Equ. 11 $S = P + jQ$

Equ. 12 $P = |S| \times \cos \varphi$

Equ. 13 $Q = |S| \times \sin \varphi$

Where: S: Apparent power
P: Active power
Q: Reactive power
φ: Phase angle

2.3.2 *Examples*

Fig. 5 shows an example of generated power with input parameters (among others) according to:

- Number of wind turbines: 3
- Maximum power per wind turbine: 150 kW

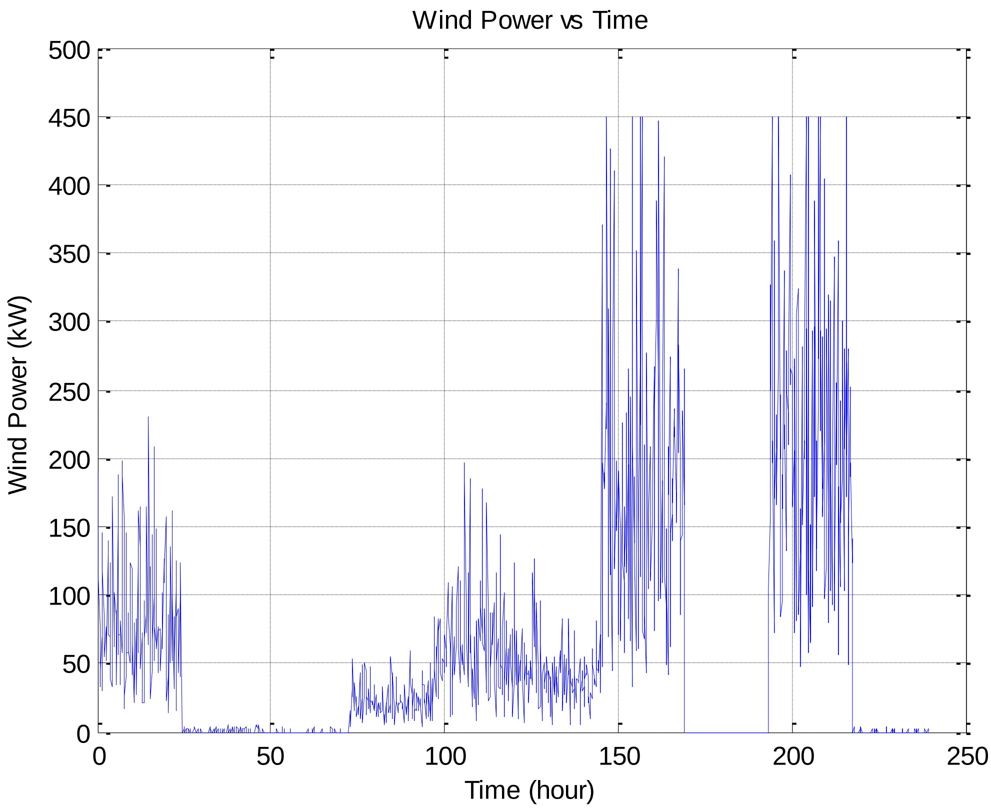

Fig. 5. Generated wind active power with input parameters according to the list above.

2.3.3 Input/Output parameters

Input parameters to the module:

- Number of wind turbines in the wind power farm
- Optimal value of tip speed ratio
- Maximum power per wind turbine
- Maximum rotation speed of wind turbine

- Total efficiency of wind turbine
- Phase angle
- Air temperature
- Air pressure
- Turbine rotor diameter
- Maximum wind speed for power production
- Minimum wind speed for power production

Output parameter from the module:

- Statistically active wind power
- Statistically reactive wind power
- Statistically apparent wind power

2.4 Module Extinction_make

2.4.1 General description

The program module “Extinction_make” generates stochastical extinction coefficients. The extinction coefficient is defined according to Equ. 14 - Equ. 17 and is a measure of atmospheric absorption regarding the solar radiation.

Equ. 14 $$\tau = \exp(-\varepsilon \cdot M)$$

Equ. 15 $$G = G_0 \times \tau$$

Equ. 16 $$M = h1 / h0$$

Equ. 17 $$M = 1 / \sin \alpha$$

Where:

τ: Atmospheric transmission coefficient (0 – 1)
ε: Extinction coefficient

M: Relative atmospheric depth (optical depth) related to the depth when sun is at zenith
$G_{0:}$ Irradiance (W/m^2) before passing the atmosphere
G: Irradiance (W/m^2) after passing the atmosphere
α: Sun altitude above horizon
h0: Atmospheric depth for $\alpha = 90^{\circ}$
h: Atmospheric depth

See Fig. 6.

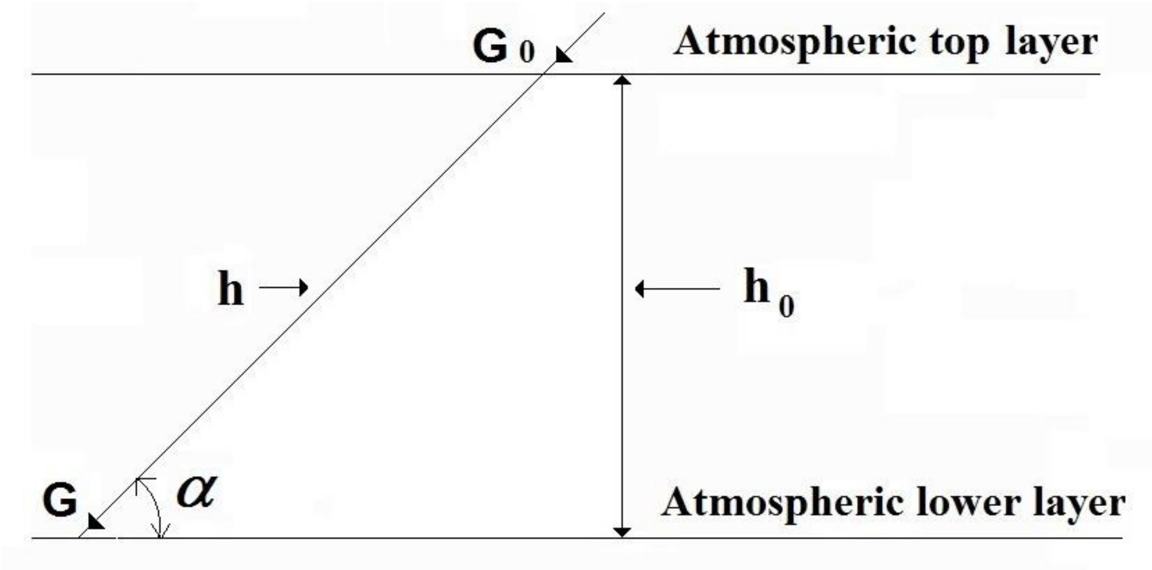

Fig. 6. Radiation G as an effect of atmospheric influence.

A more detailed description of the extinction coefficient is giveb in [2].

The extinction coefficient is devided int two components according to:

Equ. 18 $\varepsilon = \varepsilon_B + \varepsilon_N$

Where: ε: Total extinction coefficient
ε_B: Base component
ε_N: Noise component

The base component (ε_B)is divided into two modes depending on the external meteorological conditions:

- Mode 1: Solar radiation is not affected by clouds

- Mode 2: Solar radiation is affected by clouds

For stochastical generation in mode 1 the following is applied:

- Gaussian distribution
- Interval 0.32 – 0.55
- Mean value 0.43
- Standard deviation 0.048

For stochastical generation in mode 2 the following is applied:

- Trapezoidal distribution
- Interval 0.55 – 4.55
- A = 0.55, B = 4.55, P(A) = 0.4, P(B) = 0.1

Regarding the Trapezoidal distribution see Fig. 7.

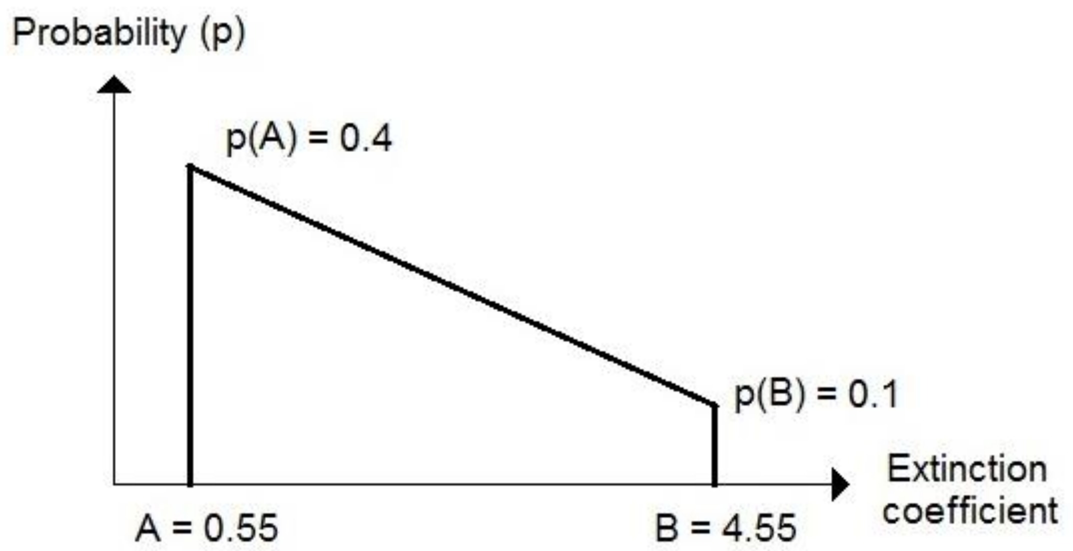

Fig. 7. The Trapezoidal distribution for generation of extinction coefficient in mode 2.

During the simulation, it is appropriate to use a combination of Mode 1 and Mode 2. This is done as follows:

- Simulation according mod 1 during time interval t1
- Simulation according mod 2 during time interval t2

Equ. 19 $$t1 = (t1+t1) \times \frac{100-p(cloud)}{100}$$

Equ. 20 $$t2 = (t1+t1) \times \frac{p(cloud)}{100}$$

Where:

t1: Simulation time according to mode 1
t2: Simulation time according to mode 2
p(cloud): Expected cloudiness in percentage

To get a good statistical confidence of the simulation result, mode 1 and mode 2 shall be updated a number of times. This is done 10 times during a total simulation process.

The noise component (ε_N) is given according to:

Equ. 21 $$\varepsilon_N = \varepsilon_B \times C\varepsilon$$

Where $C\varepsilon$ is a factor stochastical generated by a Laplace distribution that is defined according to:

Equ. 22 $$p(x) = \frac{\mathbf{1}}{\mathbf{2}\cdot \emptyset} \times \exp\left(- \frac{|\boldsymbol{x} - \boldsymbol{\theta}|}{\emptyset}\right)$$

The Laplace parameters have been chosen to:

$\emptyset = 0.0631$
$\theta = 0$

Fig. 8 shows the Laplace distribution with these parameters.

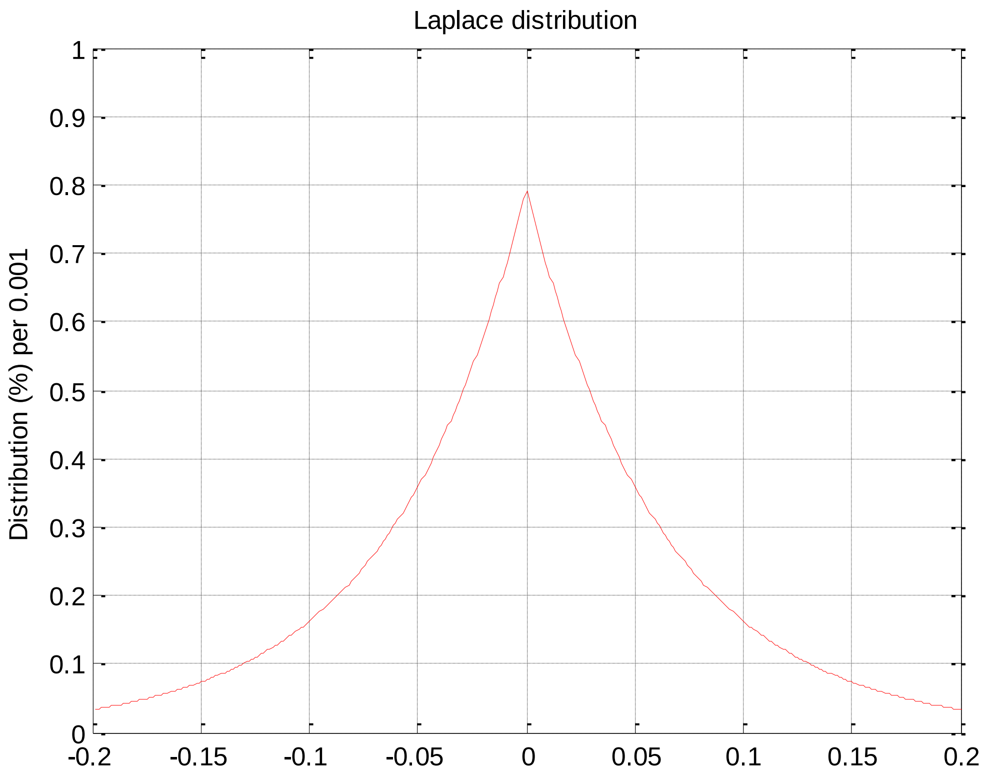

Fig. 8. Laplace distribution with ø = 0.0631 and θ = 0.

The updating routines for stochastical generation of the extinction coefficients are illustrated in Fig. 9.

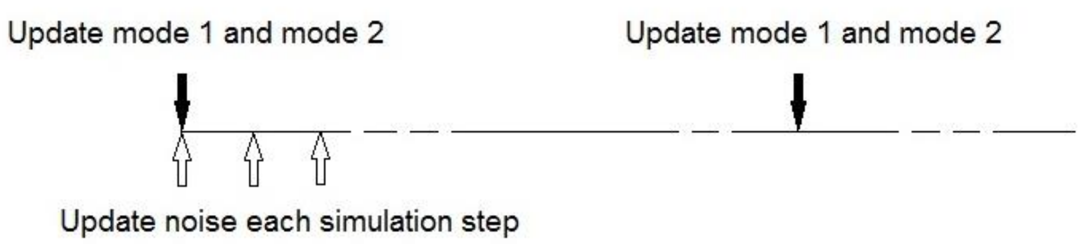

Fig. 9. Updating routines for stochastical generation of the extinction coefficients.

2.4.2 Examples

Fig. 10 shows an simulated example of extinction coefficients with expected cloudiness of 70%.

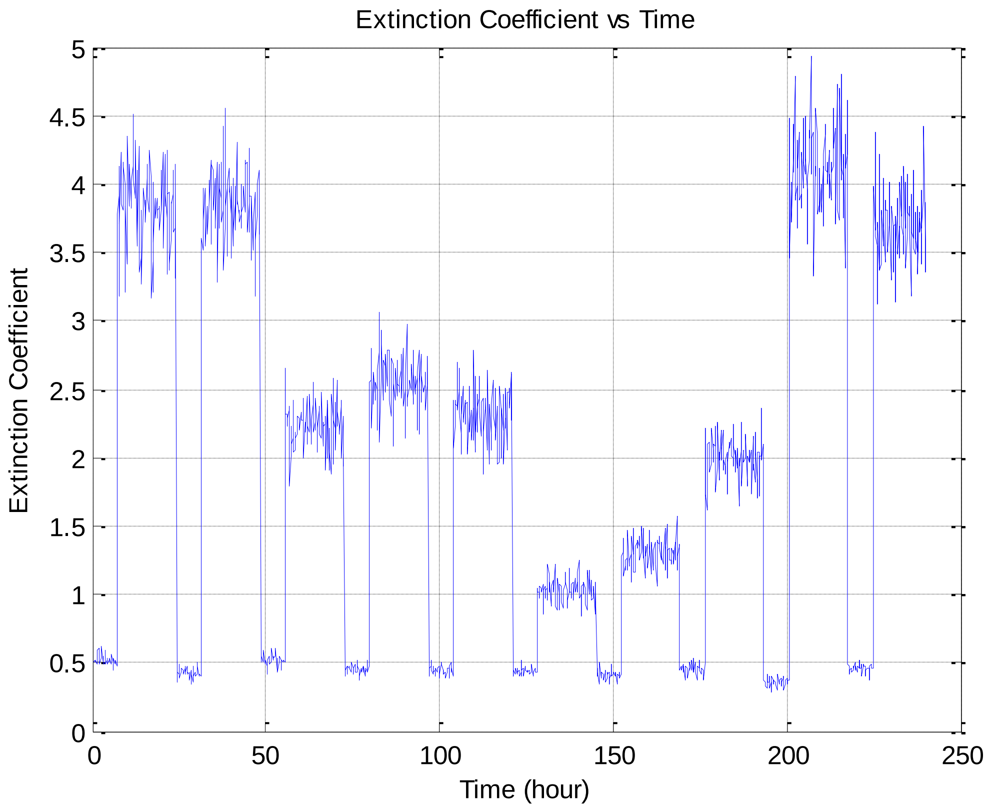

Fig. 10. Simulated extinction coefficients with expected cloudiness of 70%.

2.4.3 Input/Output parameters

Input parameter to the routine:

- Expected cloudiness

Output parameter from the routine:

- Stochastical extinction coefficients to module Sun_intensity

2.5 Module Sun_intensity

2.5.1 General description

The program module “Sun_intensity” generates the solar irradiance (W/m^2) in question. This is based on the following:

- Extinction coefficients from module “Extinction_make”
- Date and time
- Longitude and latitude
- Solar cell angle relative to the zenith and south, or information about eventually sun tracking
- Masking effects against sun radiation

2.5.2 *Basic equations*

The module is based on a number of basic equations to calculate the solar irradiance.

Equ. 23 UT = star_hour + time_counter/60 × count_interval

Where:

- UT: ”Universal Time” expressed in hours + decimals
- start_hour : Start hour for simulation (0 if the simulation will start at midnight)
- time_counter : Simulation step in question. This parameter will step from 1 up to an uper limit named time_counter_limit
- count_interval : Simulation interval per step. This parameter is specified in minutes or parts of a minute

Equ. 24 time_counter_limit = 60 × (stop_hour – start_hour) / count_interval

Where:

- time_counter_limit: upper limit for simulation steps
- *stop_hour* : stop hour for the simulation (24 if the simulation is to be performed during 24 hours, 240 if the simulation is to be performed during 10 days, and so on)

Equ. 25 $d = 367 \times y - \text{floor}(7 \times (y + \text{floor}((m + 9) / 12)) / 4) +$
$+ \text{floor}(275 \times m / 9) + D - 730530 + UT / 24$

Where:

- d: day number from 2000, Jan 01
- y: year in question (e.g. 2015)
- *m* : month in question (month number)
- *D* : date (day number in the month)

Note: floor(x) rounds “x” down to the nearest integer.

Equ. 26 $ecl = 23.4393 - 3.563 \times 10^{-7} \times d$

Where:

- ecl : “the obliquity of the ecliptic”, i.e. the “tilt” of the Earth’s axis of rotation (currently ca 23.4 degrees and slowly decreasing)

<u>Orbital elements of the Sun. These elements are partly used in the calculation of the sun position</u>:

- *N* : longitude of the ascending node
- *i* : inclination to the ecliptic (plane of the Earth’s orbit)
- *w* : argument of perihelion
- *a* : semi-major axis, or mean distance from Sun
- *e* : eccentricity (0=circle, 0-1=ellipse, 1=parabola)
- *M* : mean anomaly (0 at perihelion; increase uniformly with time)

In this case the following is relevant:

- *N* = 0.0
- *i* = 0.0

Equ. 27 $w = 282.9404 + 4.70935 \times 10^{-5} \times d$

- a = 1.0

Equ. 28 $e = 0.016709 – 1.15 \times 10^{-9} \times d$

Equ. 29 $M = 356.0470 + 0.9856002585 \times d$

<u>Compute the eccentric anomaly *E* from the mean anomaly *M* and from the eccentricity *e* (*E* and *M* in degrees)</u>:

Equ. 30 $E = M + e \times (\frac{180}{\pi}) \times \sin(\frac{M}{180}) \times (1.0 + e \times \cos(\frac{M}{180}\pi))$

<u>Compute the Sun's distance r and its true anomaly v from</u>:

Equ. 31 $Xv = r \times \cos(\frac{v}{180}\pi) = \cos(\frac{E}{180}\pi) - e$

Equ. 32 $Yv = r \times \sin(\frac{v}{180}\pi) = \sqrt{1.0 - e^2} \times \sin(\frac{E}{180}\pi)$

Equ. 33 $v = \text{atan2}(Yv, Xv) \times \frac{180}{\pi}$

Note: atan2 is a function that converts a coordinate pair to the correct angle in all four quadrants.

Equ. 34 $r = \sqrt{Xv^2 + Yv^2}$

<u>Compute the Sun's true longitude, lonsun</u>:

Equ. 35 lonsun = v + w

Convert lonsun and r to ecliptic rectangular geocentric coordinates Xs and Ys

Equ. 36 $Xs = r \times \cos(\frac{lonsun}{180}\pi)$

Equ. 37 $Ys = r \times \sin(\frac{lonsun}{180}\pi)$

As Sun is in the ecliptic plane, Zs is zero. Xs and Ys is the Sun's position in a coordinate system in the plane of the ecliptic.

Convert to equatorial, rectangular, geocentric coordinates:

Equ. 38 $Xe = Xs$

Equ. 39 $Ye = Ys \times \cos\left(\frac{ecl}{180}\pi\right)$

Equ. 40 $Ze = Ys \times \sin(\frac{ecl}{180}\pi)$

Compute Sun's Right Ascension (RA) and Declination (Dec):

Equ. 41 $RA = atan2(Ye, Xe) \times \frac{180}{\pi}$

Equ. 42 $Dec = atan2(Ze, \sqrt{Xe^2 + Ye^2} \times \frac{180}{\pi}$

Compute Sun's mean longitude, L:

Equ. 43 $L = M + w$

Compute "the Sidereal Time at Greenwich", GMST0, at 00:00 "Universal Time":

Equ. 44 $GMST0 = L + 180$

GMST0 is expressed in degrees to simplify the computations. GMST0 = 360 degrees corresponds to 24 hours, i.e. each hour corresponds to 15 degrees.

Compute Local Sidereal Time, LST:

Equ. 45 $LST = GMST0 + UT \times 15.0 + long$

Where:

- UT : "Universal Time" expressed in hours + decimals
- Long : local longitude in degrees. East longitude counts as positive and west longitude as negative

Compute Sun's Local Hour Angle, LHA, i.e. the angle the Earth has turned since the Sun last was in south:

Equ. 46 $LHA = LST - RA$

Compute Sun's altitude above the horizon, alpha:

Equ. 47 sin_alpha = $\cos(\frac{Dec}{180}\pi) \times \cos(\frac{lat}{180}\pi) \times \cos(\frac{LHA}{180}\pi) +$

$+ \sin(\frac{Dec}{180}\pi) \times \sin(\frac{lat}{180}\pi)$

Where:

- *lat* : the latitude in question

Equ. 48 alpha = arcsin(sin_alpha) (radians)

<u>Compute Sun's azimuth, az</u>:

Equ. 49 cos_az =

$$= \frac{\cos\left(\frac{Dec}{180}\pi\right) \times \sin\left(\frac{lat}{180}\pi\right) \times \cos\left(\frac{LHA}{180}\pi\right) - \sin\left(\frac{Dec}{180}\pi\right) \times \cos\left(\frac{lat}{180}\pi\right)}{\cos(alpha)}$$

Equ. 50 az = arccos(cos_az) (radians)

Equ. 23 - Equ. 50 are based on information from [3].

<u>Compute the "atmospheric depth" as a function of Sun's altitude above the horizon, alpha</u>:

Equ. 51 M_atm = $\frac{1}{\sin(alpha)}$

Where:

- M_atm: atmospheric depth relative to the depth when Sun is in zenith

Compute atmospheric transmission, τ:

Equ. 52 $\tau = \exp(-\,\mathcal{E} \times M\_atm)$

Where:

- $\mathcal{E}$: Extinction coefficient

Compute Sun irradiation to the measuring surface (solar cell):

Equ. 53 Irradiation_A = τ × Irradiation_ref

Where:

- Irradiation_A : Sun irradiation after passing the atmosphere
- Irradiation_ref : Sun irradiation before passing the atmosphere

Compute the angle, beta, between the direction to Sun and the measuring surface normal (the surface that corresponds to the solar cell panel):

Equ. 54 $$cos\_beta = \sin(alpha) \times \cos\left(\frac{Srf\_rel\_Z}{180}\pi\right) + \cos(alpha) \times \sin\left(\frac{Srf\_rel\_Z}{180}\pi\right) \times \cos\left(\frac{Srf\_rel\_S}{180}\pi\right)$$

Where:

- Srf_rel_Z : normal angle of measuring surface relative to zenith
- Srf_rel_S : normal angle of measuring surface relative to south

Equ. 55 beta = arccos(cos_beta)

<u>Compute the ”effective irradiation” from Sun against the measuring surface as a function of angle beta</u>:

Equ. 56 Irradiation_B = Irradiation_A × cos_beta

Where:

- Irradiation_B: Effective irradiation
- Irradiation_A: to surface incoming irradiation

2.5.3 *Function for “Sun Tracking”*

There is a function in the module that simulates so called “Sun Tracking”. This means that the measuring surface follows the Sun position, i.e. the angle, beta, is assigned the value zero. To get “Sun Tracking” activated the parameter “Tracking” should be assigned the value 1.

2.5.4 Properties regarding clear view between Sun and measuring surface

If there is no clear view between the sun and the measuring surface the calculated irradiance is assigned the value zero. Two equations should be fulfilled for clear view:

Equ. 57 alpha ≥ alpha_min

Equ. 58 azimuth_min ≤ az ≤ azimuth_max

Where:

- alpha: Sun’s altitude above horizon
- alpha_min: under limit for altitude of Sun to be visible
- azimuth_min: under limit for azimuth of Sun to be visible
- azimuth_max: upper limit for azimuth of Sun to be visible

2.5.5 *Examples*

Table 2 give three examples of locations with corresponding latitudes and longitudes. These latitudes and longitudes have been used as input parameters to the module. The resulting values on irradiances are shown in Table 3. The calculations presumes cloudless sky.

Table 2. 3 examples of location.

Location	**Latitude (degrees)**	**Longitude (degrees)**
Nairobi	-1.283	36.833
Kiruna	67.850	20.217
Göteborg	57.710	11.968

Table 3. Integrated (per month)irradiance.

Month	**Integrated irradiance (kWh/m^2) Nairobi**	**Integrated irradiance (kWh/m^2) Göteborg**	**Integrated irradiance (kWh/m^2) Kiruna**
January	260.36	32.06	0.16
February	264.96	91.08	27.43
Mars	266.68	165.52	111.65
April	263.51	244.25	218.98
May	257.33	302.48	304.27
June	253.12	330.93	348.99
July	255.08	318.29	328.74
August	261.27	269.22	254.84
September	266.08	197.15	153.59
October	266.05	117.67	53.70
November	261.92	47.57	2.42
December	258.61	18.41	0
Total year	3135	2135	1805

Fig. 11 shows the integrated irradiance per single month during the year with cloudless sky for Nairobi, Göteborg and Kiruna.

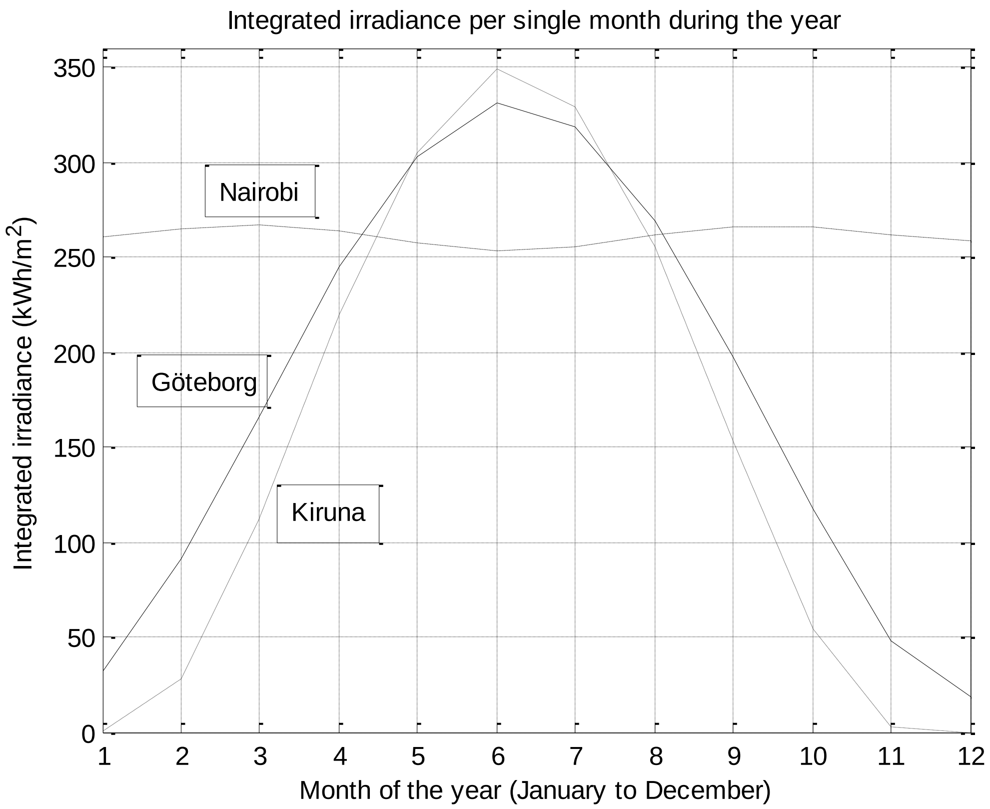

Fig. 11. Integrated irradiance during the year with cloudless sky for Nairobi, Göteborg and Kiruna.

Fig. 12 shows a sample of simulated effective irradiance to a measuring surface (solar cell) with (among others) following inputs:

- Date: June 21
- Longitude: 11.968 (Göteborg, Sweden)
- Latitude: 57.710 (Göteborg, Sweden)
- Normal angle of measuring surface (solar cell) relative to south: - 27º
- Normal angle of measuring surface (solar cell) relative to zenith: 0º
- Cloudiness 50% (input to module ”Extinction_make” that gives the extinction coefficients to module “Sun_intensity”)

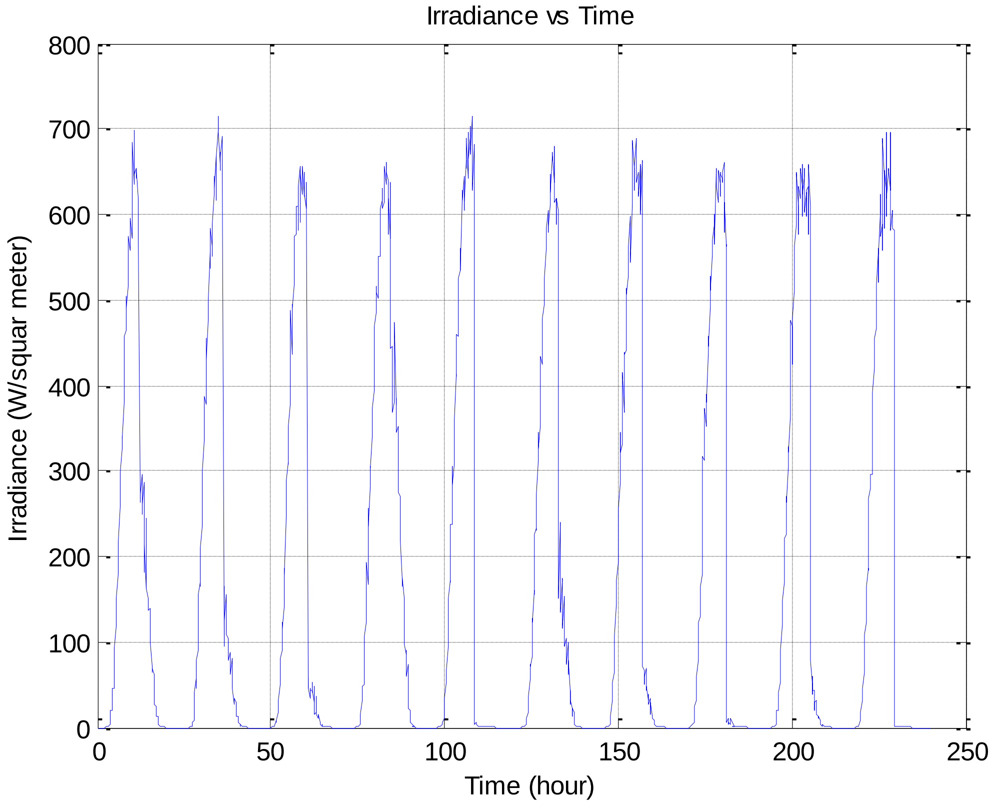

Fig. 12. Simulated irradiance with input parameters according to the list above.

2.5.6 Input/Output parameters

Input parameters to the module:

- Date
- Time
- Longitude
- Latitude
- Normal angle of measuring surface (solar cell) relative to south. An alternative is to use the function “Sun Tracking”. See section 2.5.3.
- Normal angle of measuring surface (solar cell) relative to zenith. An alternative is to use the function “Sun Tracking”. See section 2.5.3.
- alpha_min. See section 2.5.4.
- azimuth_min. See section 2.5.4.
- azimuth_max. See section 2.5.4.
- Extinction coefficients (from module ”Extinction_make”

Output parameters from the module:

- Effective irradiance (to module “Sun_panel_generator”)

2.6 Module Sun_panel_generator

2.6.1 General description

The program module “Sun_panel_generator” calculates the electric power from a specified number of solar panels. The calculation is performed according to:

Equ. 59 $Ps = G \times A \times Pfs$

Equ. 60 $Pfs = Pf1 \times Pf2 \times Pf3$

Where:

Ps: Generated active solar power (W)
G: Irradiation (W/m^2)
A: Total solar cell area (m^2)
Pfs: Solar power farm efficiency
Pf1: Solar cell efficiency
Pf2: Maximum Power Point (MPP) efficiency. MPP is the position in the solar cell voltage/current characteristic, where the product voltage × current is maximized.
Pf3: Power electronics efficiency

Generated reactive power is a function of the “Phase Angle”. See Equ. 11, Equ. 12 and Equ. 13.

2.6.2 Examples

Fig. 13 shows an example of generated active power from a solar cell farm with (among others) following input parameters:

- Total solar cell area: 3000 m^2
- Solar cell efficiency: 15 %
- Maximum Power Point (MPP) efficiency: 95 %
- Power electronics efficiency: 95 %

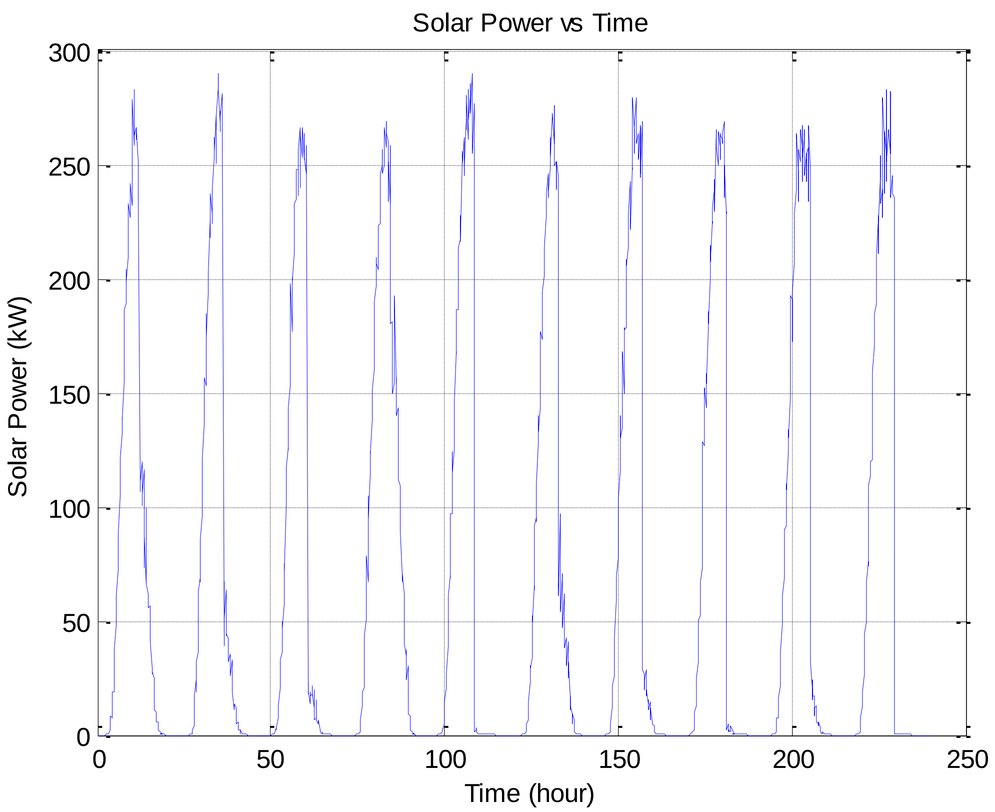

Fig. 13. Example of generated active solar power with input parameters according to the list above.

2.6.3 Input/Output parameters

Input parameters to the module:

- Effective irradiance from module "Sun_intensity"
- Total solar cell area
- Solar cell efficiency
- Maximum Power Point (MPP) efficiency
- Power electronics efficiency: 95 %
- Phase angle

Output parameter from the module:

- Statistically active solar power
- Statistically reactive solar power
- Statistically apparent solar power

2.7 Module Load_make

2.7.1 General description

The program module "Load_make" calculates stochastic electrical load, consisting of two components, active power and reactive power:

Equ. 61 $S = P + jQ$

Where: S: Apparent power
P: Active power
Q: Reactive power

Equ. 62 $P = |\mathbf{S}| \times \cos \varphi$

Equ. 63 $Q = |S| \times \sin \varphi$

Where: φ: Phase angle

$|S|$ is divided into two Gaussian distributed power components:

$|\mathbf{S}| = S_L + S_H$

Where: S_L: Low frequency power component
S_H: High frequency power component

Equ. 64 $S_L = F1$

Equ. 65 $S_H = F2 \times S_L$

Where: F1 and F2 are Gaussian distributed functions.

3 different types of power consumers can be used. In combination or individual:

- Industrial area
- Residential area
- Commercially center

A detailed description of the module development is given in [4].

2.7.2 Industrial area

The low frequency component for an industrial area is a function of time point according to Fig. 14. The figure shows the variations during an ordinary working day. Also see section 2.7.1.

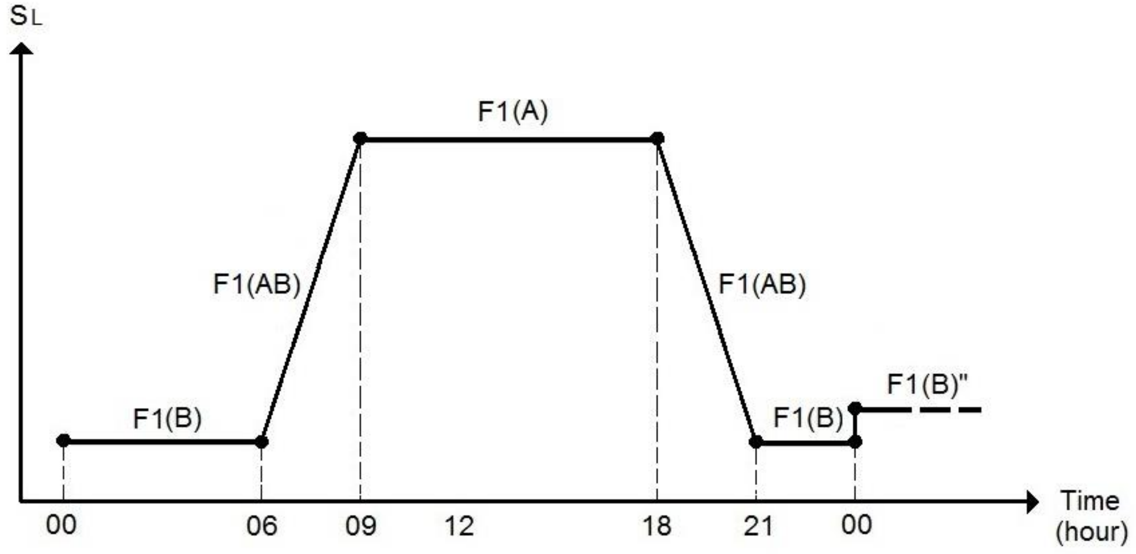

Fig. 14. Low frequency component as a function of time. Working day.

For a working day 3 classes are defined according to:

F1(A): Class A. Low frequency component, day time, working day.
F1(B): Class B. Low frequency component, evening/night time, working day.
F1(AB): Class AB. Low frequency component, transition between night time to day time resp. day time to evening time.

F1(B)” in Fig. 14 shows the low frequency component, evening/night time, for a new 24 hour cycle. This will indicate that all functions F1 are updated every new 24 hour cycle.

The low frequency component for a weekend day and an industrial area is shown in Fig. 15. F1(C)” in the figure shows the low frequency component for a new 24 hour cycle. This will indicate that all functions F1 are updated every new 24 hour cycle. Weekend days correspond to class C.

Fig. 15. Low frequency component as a function of time. Weekend day.

F1 and F2 are Gaussian distributed functions with mean values and standard deviations according to Table IV.

Table IV. Statistical Gauss parameters for an industrial area.

Class	F1		F2	
	Mean value (W)	*Standard deviation (W)*	*Mean value*	*Standard deviation*
A	K1 × 2.1091 × 10^5	K1 × 2.5107 × 10^4	0	0.04
B	K1 × 1.1333 × 10^5	K 1× 1.3462 × 10^4	-0.01	0.03
AB	Lines between F1(A) and F1(B)		0	0.04
C	K1 × 1.1278 × 10^5	K1 × 1.9269 × 10^4	0	0.04

Parameter K1 in Table IV is defined according to:

Equ. 66 $K1 = W / 1.2722 \times 10^6$

Where: W: Annual power consumption (kWh).

Updating of F1 and F2:

- F1 is updated every new 24 hour cycle
- F2 is updated every new simulation step

2.7.3 Commercially center

Low- resp high frequency component for a commercially center are defined according to Table V. Also see section 2.7.1.

Table V. Statistical Gauss parameters for a commercially center.

F1		F2	
Mean value (W)	*Standard deviation (W)*	*Mean value*	*Standard deviation*
K × 1.1278 × 10^5	K × 1.9269 × 10^4	0	0.04

Parameter K in Table V is defined according to:

Equ. 67 $K = W / 9.8795 \times 10^5$

Where: W: Annual power consumption (kWh)

Updating of F1 and F2:

- F1 is updated every new 24 hour cycle
- F2 is updated every new simulation step

2.7.4 *Residential area*

The low frequency component for a *residential* are is a function of time point according to Fig. 16. F1(B)" in the figure shows the low frequency component for a new 24 hour cycle. This will indicate that all functions F1 are updated every new 24 hour cycle.

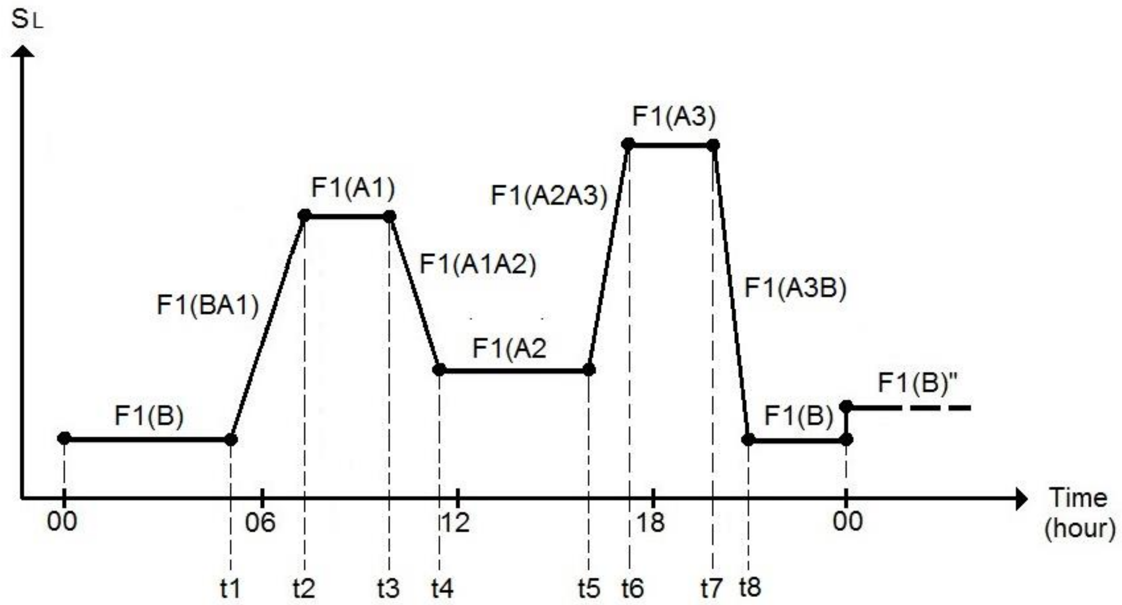

Fig. 16.   Low frequency component as a function of time.

The components are as follows:

- F1(B): low frequency component during time zones 00 – t1 and t8 – 00.
- F1(A1): low frequency component during time zone t2 – t3.
- F1(A2): low frequency component during time zone t4 – t5.
- F1(A3): low frequency component during time zone t6 – t7.
- F1(BA1): low frequency component during time zone t1 – t2.
- F1(A1A2): low frequency component during time zone t3 – t4.
- F1(A2A3): low frequency component during time zone t5 – t6.
- F1(A3B): low frequency component during time zone t7 – t8.

The transition between F1(B) – F1(A1), F1(A1) – F1(A2), F1(A2) – F1(A3) and F1(A3) – F1(B), corresponding to F1(BA1), F1(A1A2), F1(A2A3) and F1(A3B), follows the same principle as discussed in section 2.7.2 (straight line).

In the absence of good statistical basis, a preliminary attempt has been made according to the following time zones and Table VI.

Time zones:

- t1 = 5
- t2 = 7
- t3 = 10
- t4 = 12
- t5 = 15
- t6 = 17
- t7 = 21
- t8 = 22

Table VI. Statistical Gauss parameters for a residential area.

Class	**F1**		**F2**	
	Mean value (W)	*Standard deviation (W)*	*Mean value*	*Standard deviation*
A1	K × 2.5	K × 0.4271	0	0.04
A2	K × 1.5	K × 0.2563	0	0.04
A3	K × 3.5	K × 0.5980	0	0.04
B1	K	K × 0.1709	0	0.04

Parameter K in Table VITable V is defined according to:

Equ. 68 $$K = \frac{W}{17.429}$$

Where: W: Annual power consumption (kWh)

2.7.5 Examples

Fig. 17 - Fig. 19 illustrate a simulation example that covers 16 days with 12 working days and 4 weekend days. In addition there are different phase angles depending on time points, according to:

- 30˚ during working day between 06 – 21
- - 10˚ during working day between 21 – 06 and during weekend days

The figures show apparent power, active power and reactive power.

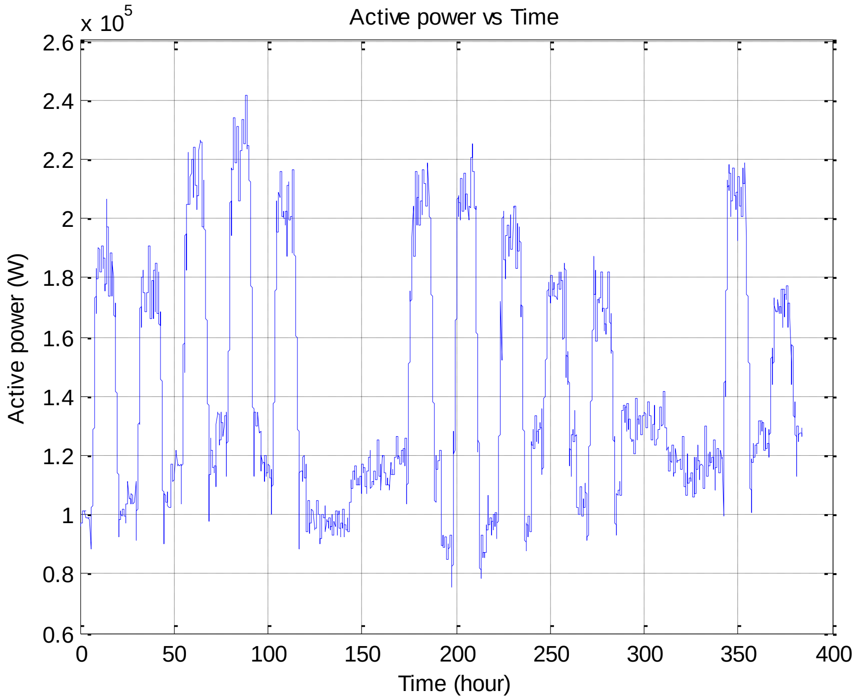

Fig. 17. Simulation example with 16 days, including 12 working days and 4 weekend days. Active power.

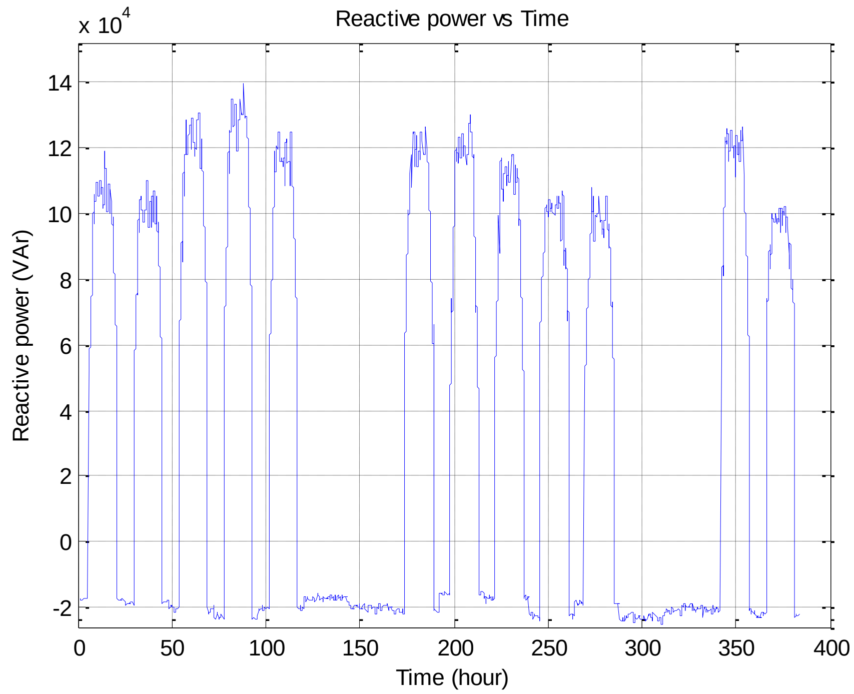

Fig. 18. Simulation example with 16 days, including 12 working days and 4 weekend days. Reactive power.

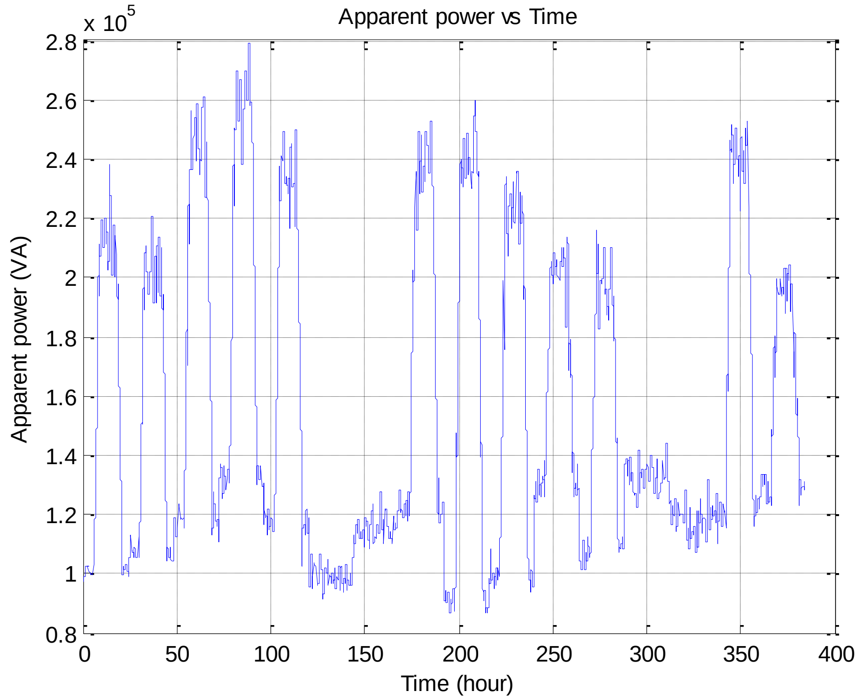

Fig. 19. Simulation example with 16 days, including 12 working days and 4 weekend days. Apparent power.

Fig. 20 shows an area consisting of 4 industrial complexes, 1 commercially center and 12 residential complexes.

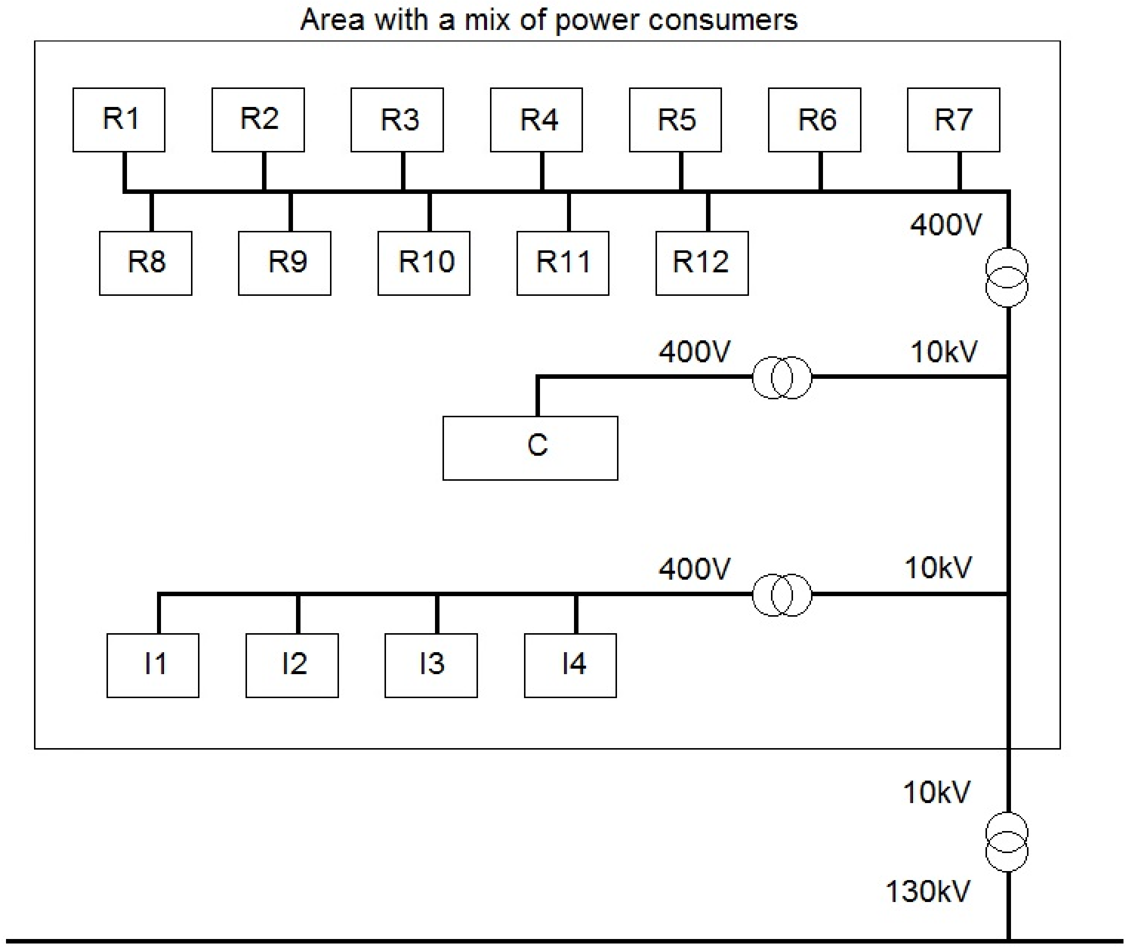

Fig. 20.   An area with a mix of power consumers.

Abbreviations in Fig. 20 are according to:

- I1 – I4: 4 industrial complexes
- C: Commercially center
- R1 –R12: 12 residential complexes

A simulation is done with following assumptions:

<u>Model for industrial area, input parameters</u>

- Annual power consumption: 1 TWh
- Phase angle, time 06 - 21 (day time): +40°
- Phase angle, time 21 – 06 (night time): + 5°

<u>Model for commercially center, input parameters</u>

- Annual power consumption: 0.5 TWh
- Phase angle: - 5°.

<u>Model for residential area, input parameters</u>

- Annual power consumption: 2 TWh
- Phase angle: + 5°.

The output result is related to total power consumption of all consumers. This corresponds to the connection point at the 130 kV-line in Fig. 20.

The simulation result for 10 days is illustrated in Fig. 21 - Fig. 23.

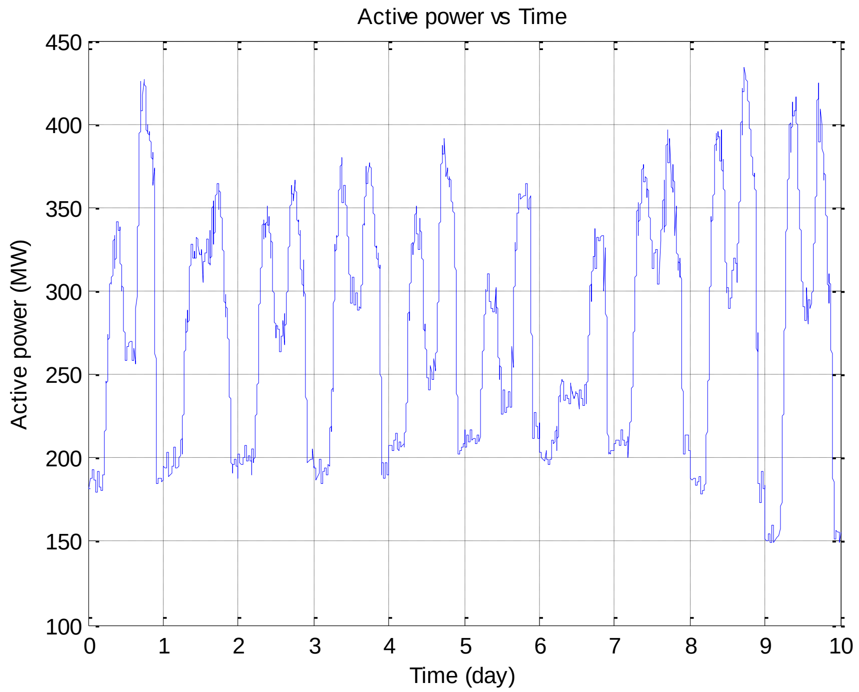

Fig. 21. Simulated active power consumption during 10 days for the area of mixed power consumers.

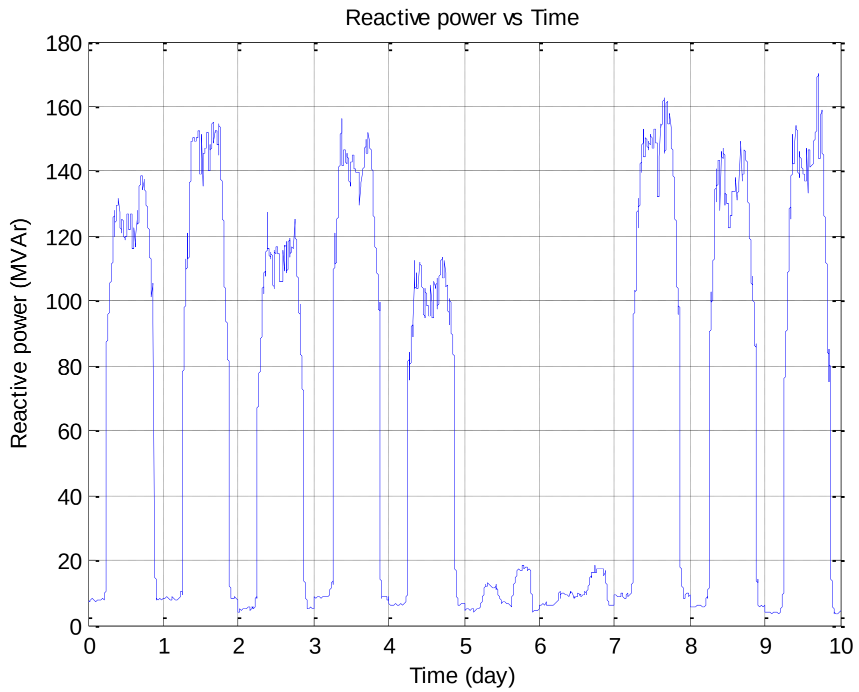

Fig. 22. Simulated reactive power consumption during 10 days for the area of mixed power consumers.

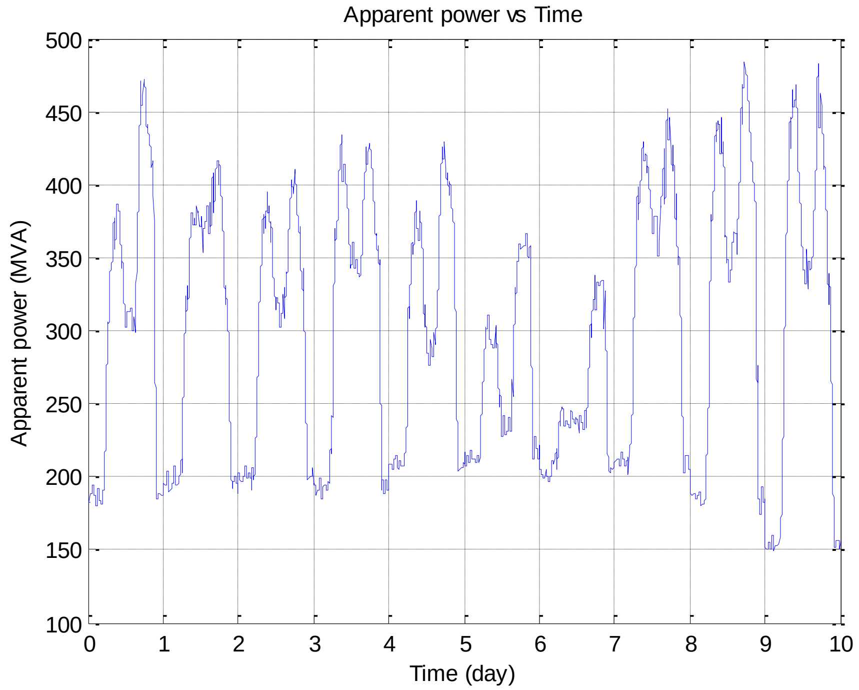

Fig. 23. Simulated apparent power consumption during 10 days for the area of mixed power consumers.

2.7.6 Input/Output parameters

Input parameters to the module:

- Annual power consumption, industrial area
- Annual power consumption, residential area
- Annual power consumption, commercially center
- Phase angle, industrial area, time 06 - 21 (day time)
- Phase angle, industrial area, time 21 – 06 (night time)
- Phase angle, residential area
- Phase angle, commercially center

Ouput parameters from the module:

- Statistically load of active power
- Statistically load of reactive power
- Statistically load of apparent power

2.8 Module Connect_Gen_load

2.8.1 General description

The program module “Connect_Gen_load” perform handling of electrical power status as a result of power production and power consumtion. The Gross power and net power is defined according to:

Equ. 69 Gross Power = Wind Power + Solar Power

Equ. 70 Net Power = Gross Power – Load Power

Where:

- Wind Power: Total generated wind power at time point
- Solar Power: Total generated solar power at time point
- Load Power: Total load at time point

2.8.2 Examples

Fig. 24 , Fig. 25 and Fig. 26 illustrate simulation examples on related values regarding Gross Power, Load Power and Net Power.

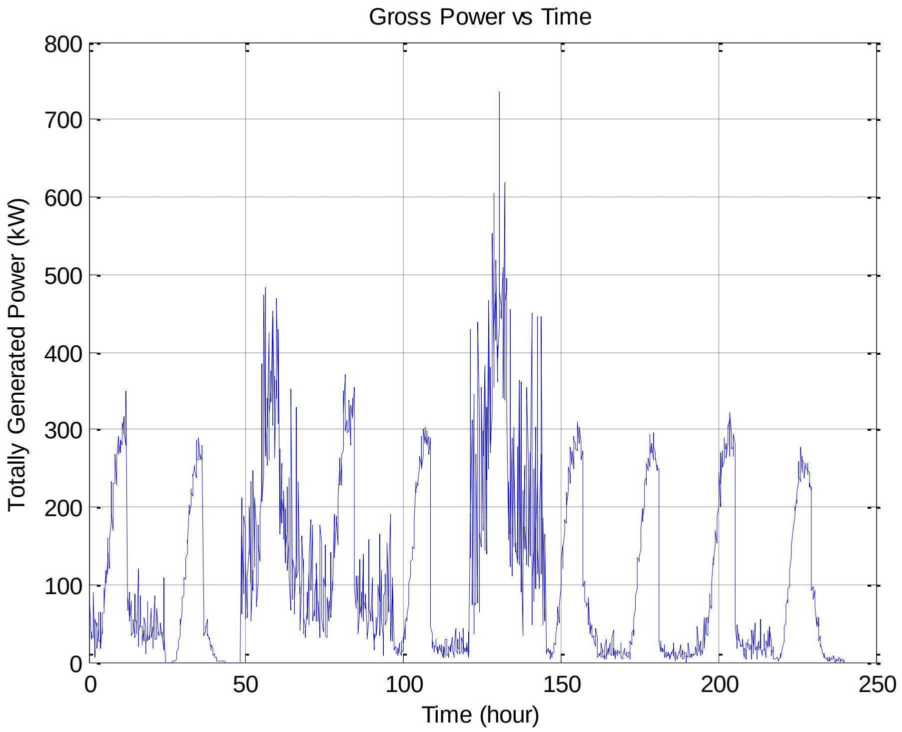

Fig. 24. Simulated example on Gross Power.

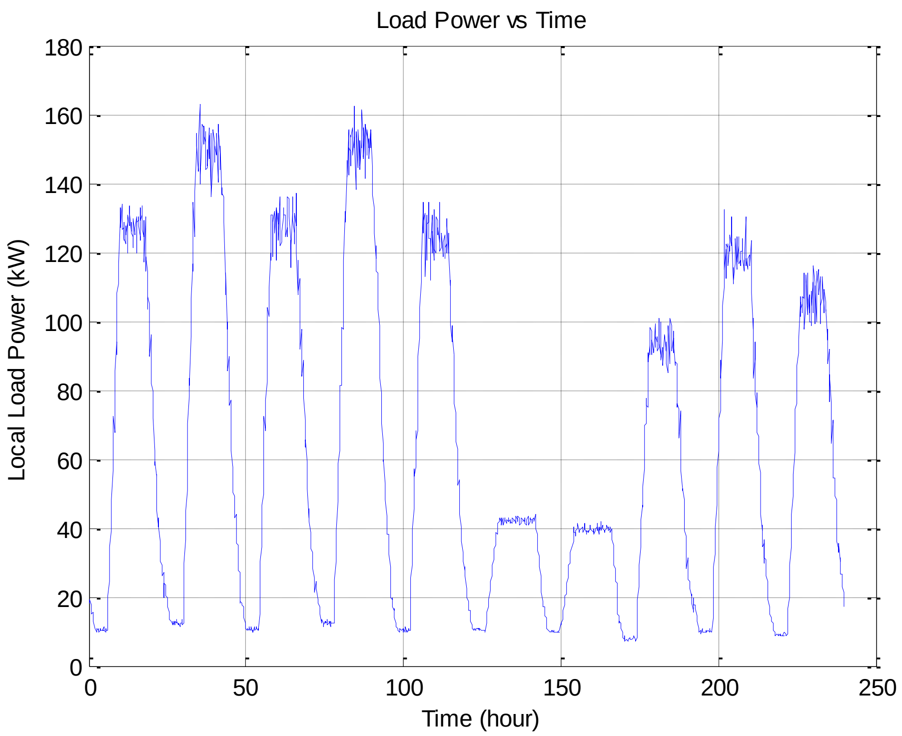

Fig. 25. Simulated example on Load power.

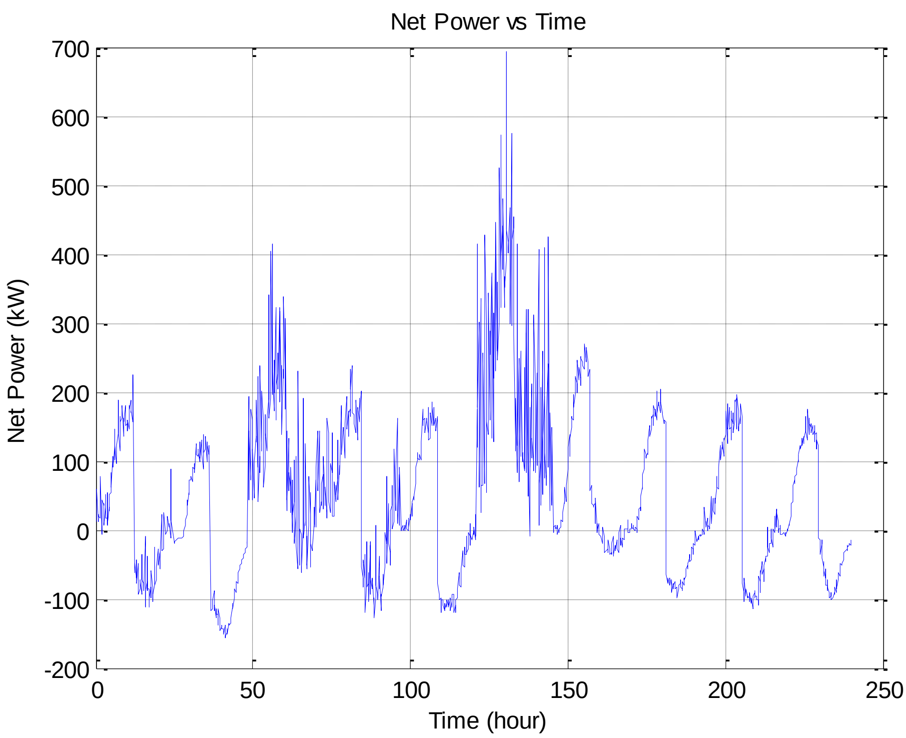

Fig. 26. Simulated example on Net Power.

2.8.3 Input/Output parameters

Input parameters to the module:

- Wind Power
- Solar Power
- Load Power

Otput parameters from the module:

- Gross Power
- Net Power

2.9 Module Storage_distribution

2.9.1 General description

The program module "Storage_distribution" perform handling of the process regarding energy storage and usage of utility grid. Two modes are defined:

- Charging / Discharging of energy storage
- Exporting/Importing energy via utility grid

2.9.2 Examples

Fig. 27, Fig. 28 and Fig. 29 illustrate simulation examples on related values regarding Energy Storage level, Exported Power and Imported Power.

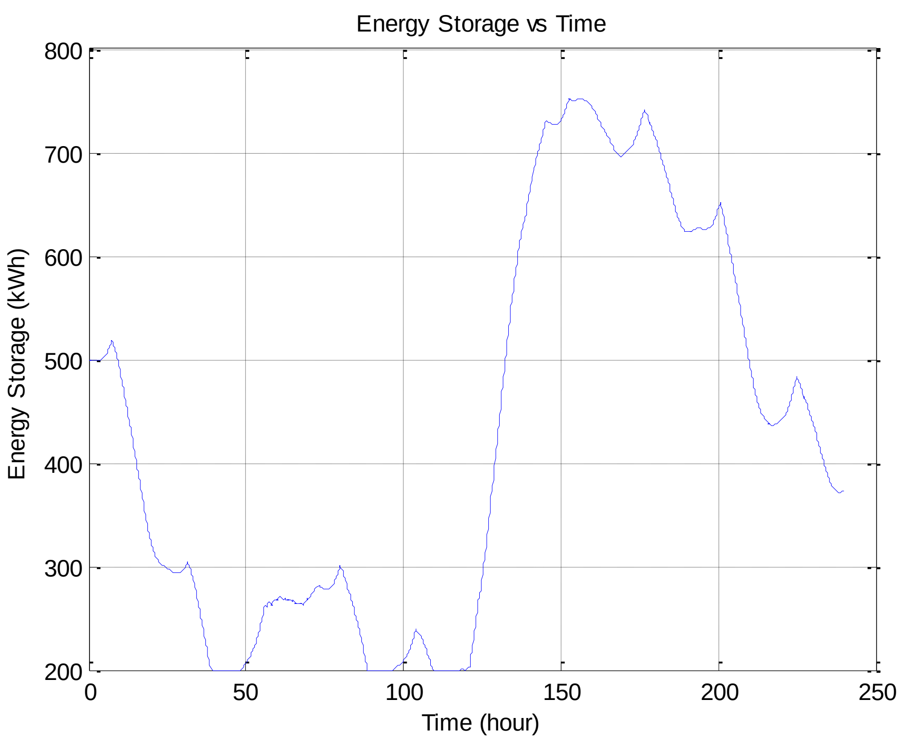

Fig. 27. Simulated example on Energy Storage level.

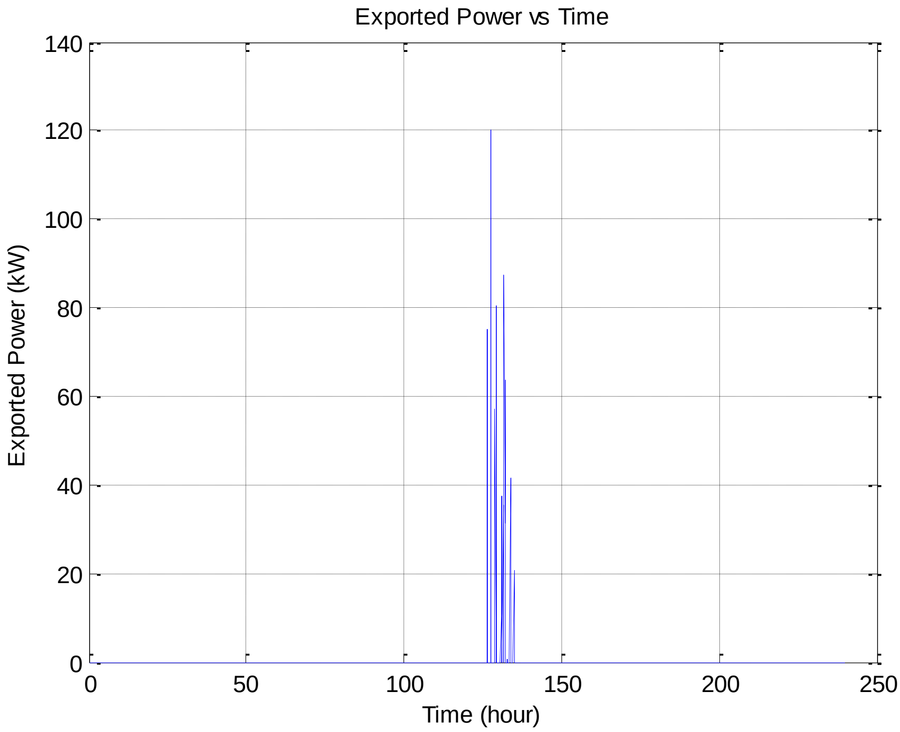

Fig. 28. Simulated example on Exported Power to utility grid vs Time.

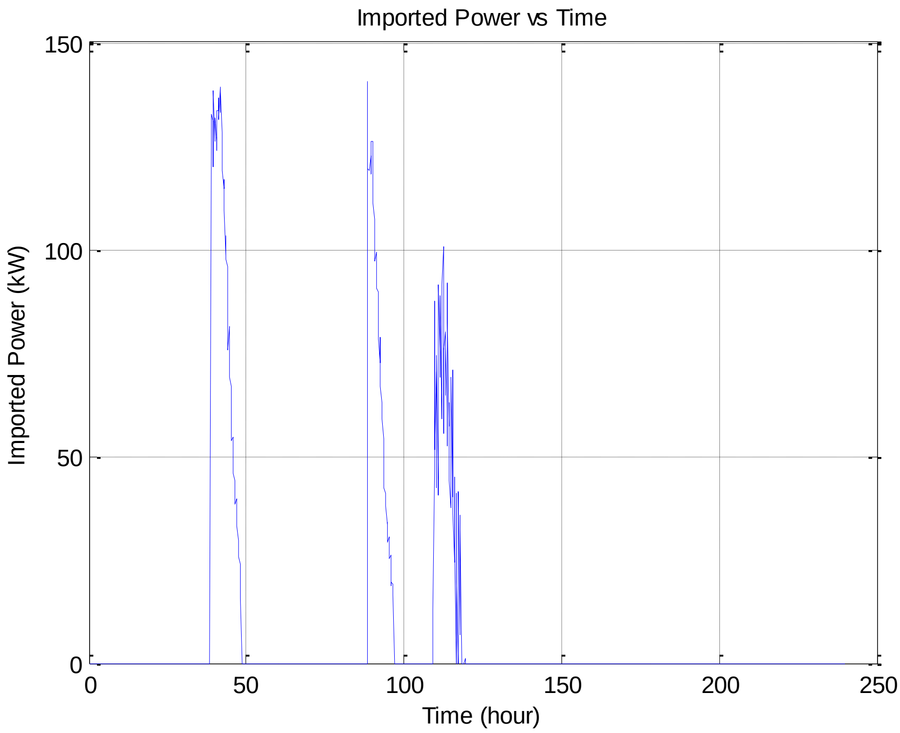

Fig. 29. Simulated example on imported Power from utility grid vs Time.

2.9.3 Input/Output parameters

Input parameters to the module:

- Charging efficiency
- Discharge efficiency
- Initial charge
- Maximum allowable charge
- Minimum allowable charge
- Self-discharge
- Maximum allowable charge/discharge power
- Maximum allowable power for export/import
- Net Power

Output parameters from the module:

- Energy Storage level
- Exported Power to utility grid
- imported Power from utility grid

2.10 Module Power_evaluate

2.10.1 General description

The program module "Power_evaluate" perform evaluation of the simulation based on all simulation repeats. The result is presentated in the form of statistical parameters.

2.10.2 Examples

Fig. 30 shows the presented result of a simulation process on 200 repeats.

E_Wind (kWh):	My = 1.561e+003	Sigma = 4.908e+002
E_Sun (kWh):	My = 7.897e+002	Sigma = 1.473e+002
E_Gen (kWh):	My = 2.351e+003	Sigma = 5.107e+002
E_Load (kWh):	My = 1.474e+003	Sigma = 7.184e+001
E_Exp (kWh):	My = 1.685e+002	Sigma = 2.918e+002
E_Imp (kWh):	My = 3.844e+001	Sigma = 7.263e+001
D_Exp_Imp (kWh):	My = 1.301e+002	Sigma = 3.182e+002
Rel_Wind_Gen:	My = 6.516e-001	Sigma = 8.718e-002
Rel_Sun_Gen:	My = 3.484e-001	Sigma = 8.718e-002
Rel_Gen_Load:	My = 1.598e+000	Sigma = 3.528e-001
Rel_Exp_Gen:	My = 5.617e-002	Sigma = 8.952e-002
Rel_Imp_Load:	My = 2.595e-002	Sigma = 4.906e-002
Rel_DEI_Gen:	My = 3.486e-002	Sigma = 1.097e-001
Rel_Battery_Load:	My = 6.801e-001	Sigma = 3.319e-002

Fig. 30. An example of presented result regarding a simulation process.

2.10.3 Input/Output parameters

Input parameters to the module:

- Wind energy
- Solar energy
- Exported energy
- Imported energy
- Load energy

Output parameters from the module:

Mean values and standard deviation regarding:

- Wind energy
- Solar energy
- Total generated energy
- Exported energy
- Imported energy
- Load energy
- Difference between generated and load energy
- Relation Wind energy / Total generated energy
- Relation Solar energy / Total generated energy
- Relation Total generated energy / Load energy
- Relation Exported energy / Total generated energy

- Relation Imported energy / Total generated energy
- Relation (Exported energy - Imported energy) / Total generated energy
- Relation Maximum allowable charge / mean value of Load energy

See also the corresponding output parameters in section 2.10.2.

3 REFERENCES

[1] Mathiasson I. “Analysis of Wind Speed”. Chalmers University of Technology, 2015.

[2] Mathiasson I. “Solar power. Statistical analysis of extinction coefficients”. Chalmers University of Technology, June 2015.

[3] Paul Schlyter, based on T. van Flandern's and K. Pulkkinen's paper "Low precision formulae for planetary positions. Algorithms to calculate planetary positions for Sun, Moon and major planets”. Published in the Astrophysical Journal Supplement Series, 1980.

[4] Mathiasson I. “Modelling of an electrical load”. Chalmers University of Technology, 2015.