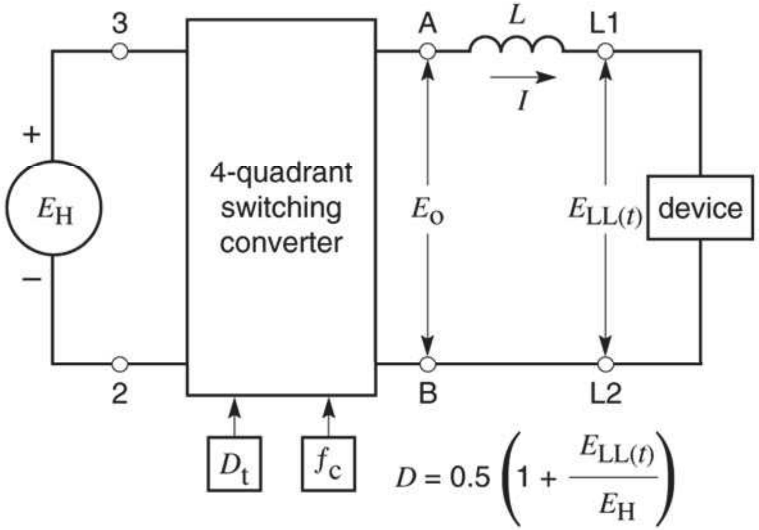
Dc-AC SINE WAVE CONVERTER



- $E_{LL} = E_H\,(2D-1)$
- E_H given
- E_{LL} requested f(t)
- $E = E_m \sin(360ft + \theta)$
- $D_{(t)} = 0.5\,[1 + E_m/E_H \sin(360ft + \theta)]$
- amplitude modulation ratio

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Example 21-14

- 200V dc source 4 q, switching converter operating at the carrier of 8kHz, desired sinusoidal 120 V 97Hz and θ=35

  - $E_m = 120\ \text{Sqrt}(2) = 170\ V$
  - $m = E_m / E_H = 170/200 = 0{,}85$
  - $m_f = f_c / f = 8000/97 = 82{,}47$
  - $D_{(t)} = 0.5\ [1 + E_m/E_H \sin(360ft + \theta)]$

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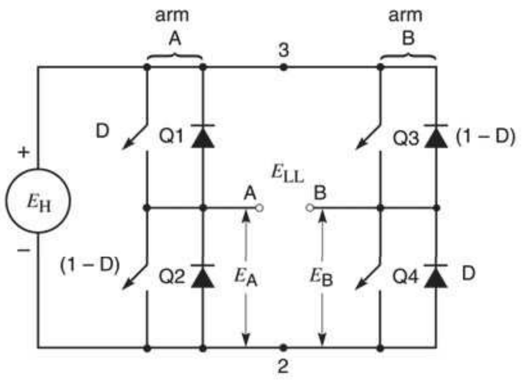
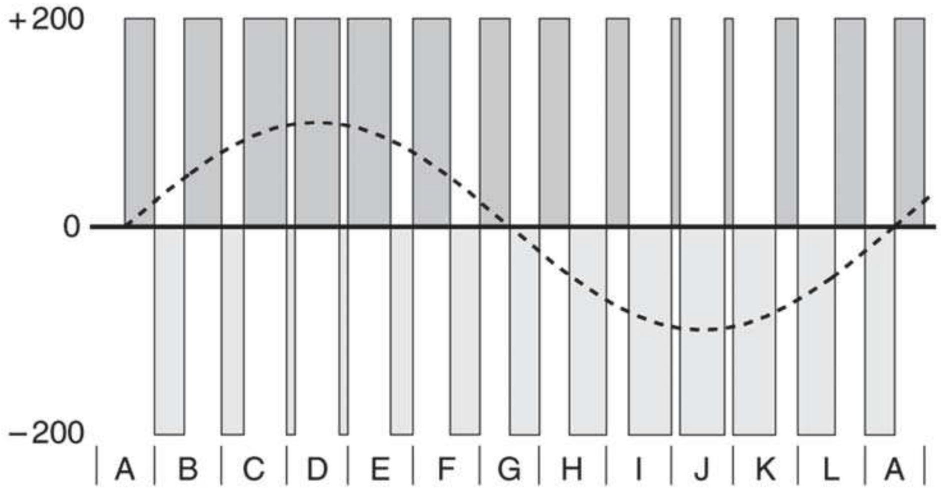
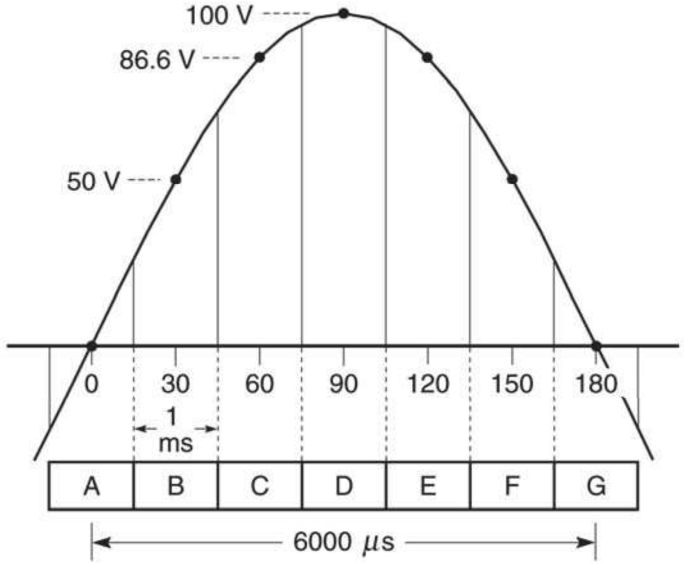
Figure 21.82 **Positive half-cycle of the fundamental 83.33 Hz voltage comprises six carrier periods of 1 ms each.**







- $D_{(t)} = 0.5\ [1+E_m/E_H)$

Figure 21.85 **A two-quadrant PWM chopper and its load. The filter eliminates the unwanted carrier frequency component.**

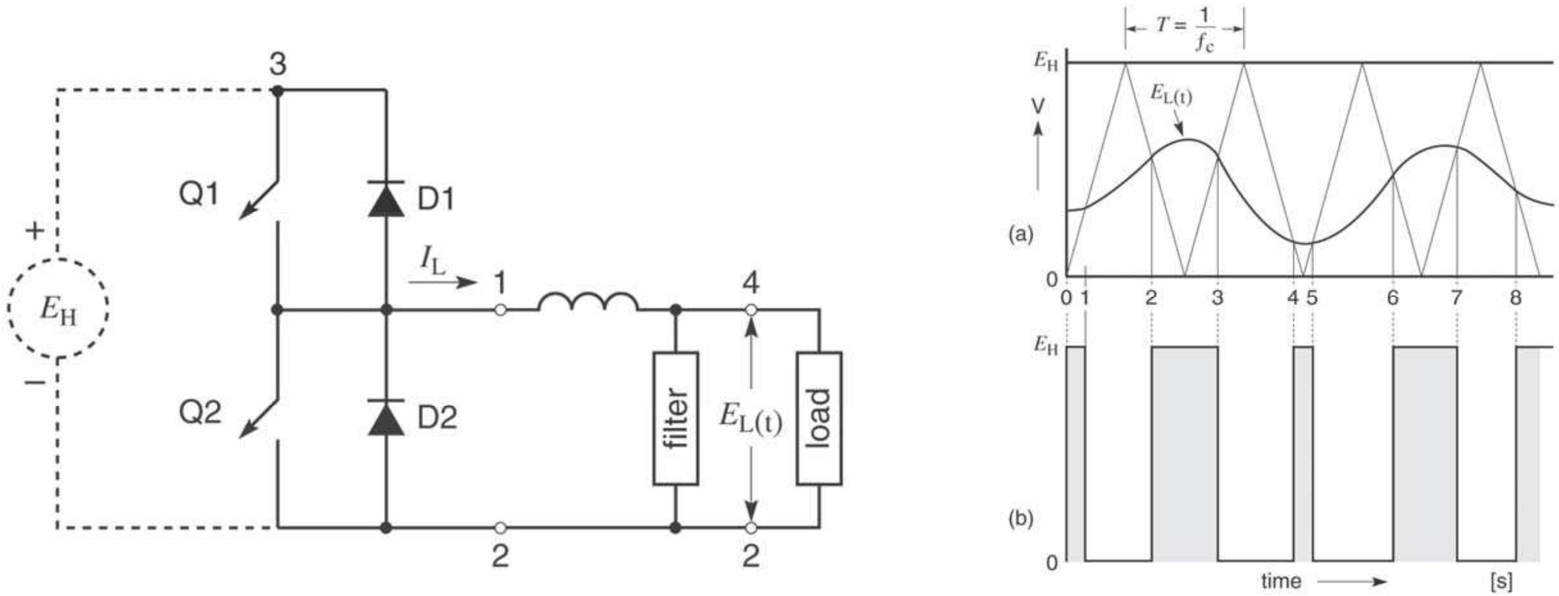
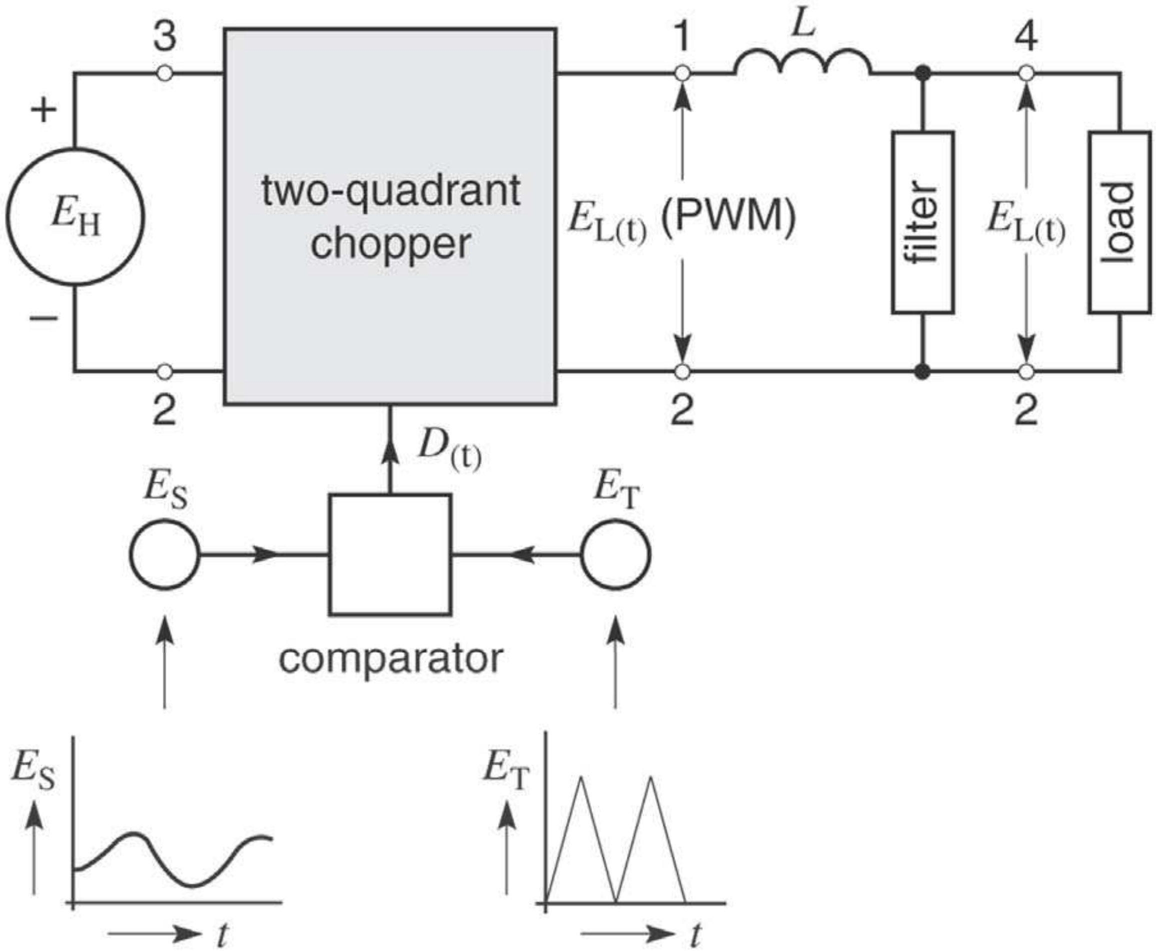
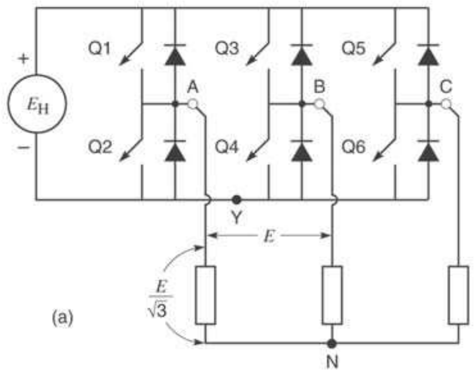


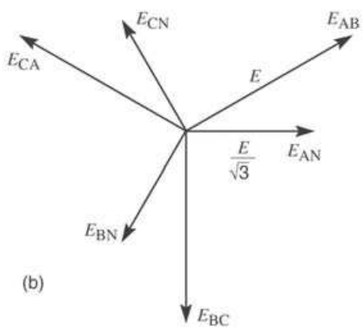
Figure 21.87 **A comparator determines the crossing points between the miniature version E_S of the wanted waveshape $E_{L(t)}$ and a triangular waveshape, thereby producing the control signal $D_{(t)}$. The signal triggers the switches in the chopper to generate the PWM waveshape that contains the wanted output $E_{L(t)}$. .**

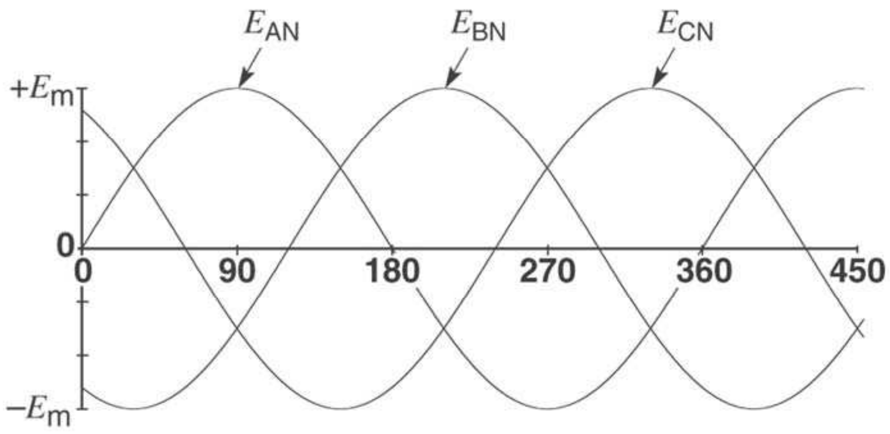


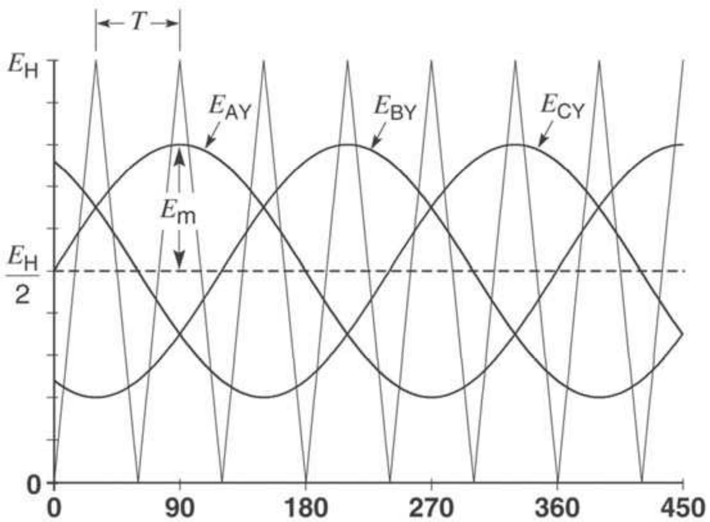
TUDelft

DC-AC 3 phase converter









TU Delft

Figure 21.91 **a. PWM pulses between terminals A and Y, and their sinusoidal E_{AY} component. b. PWM pulses between terminals B and Y, and their sinusoidal E_{BY} component.**

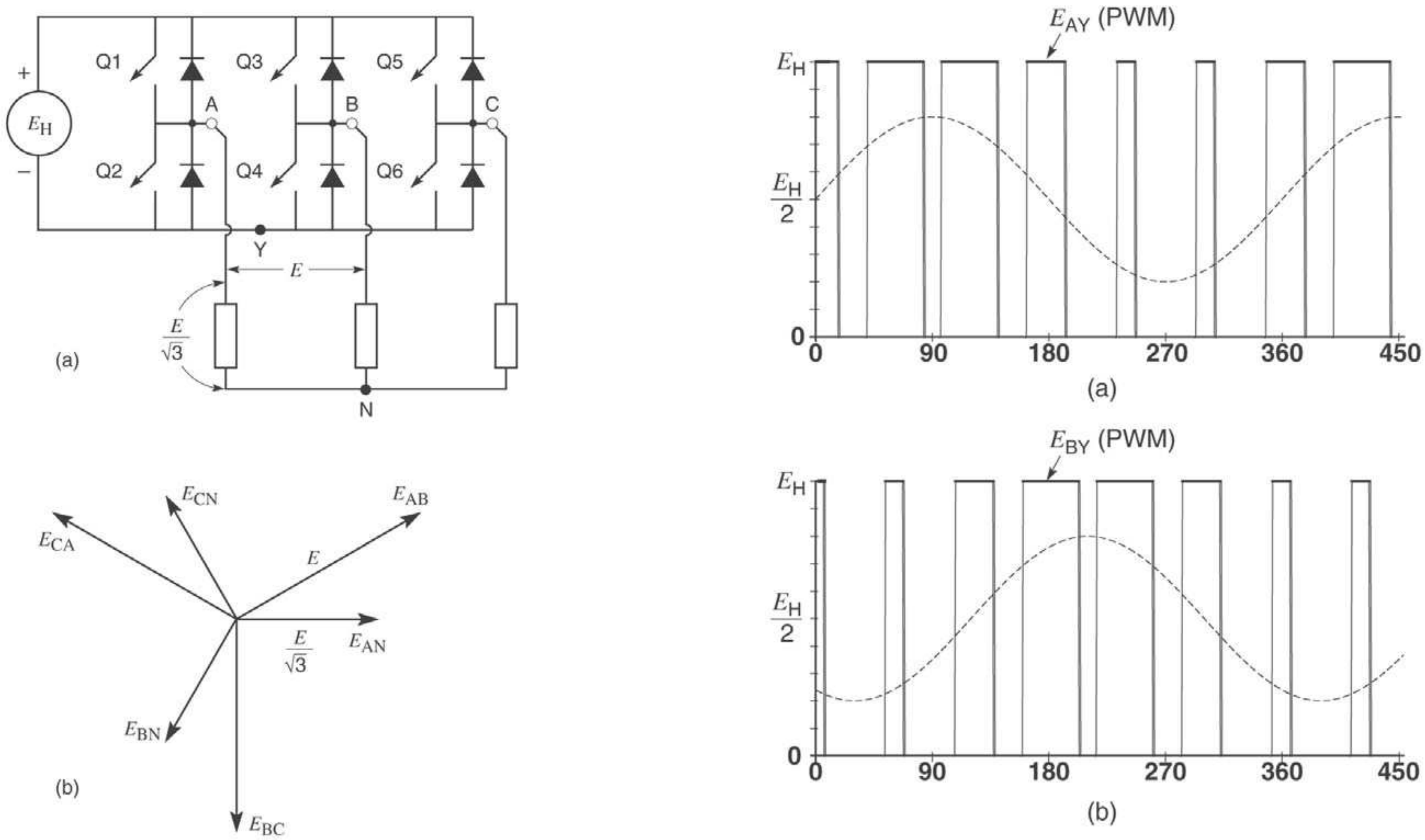


Figure 21.91 **a. PWM pulses between terminals A and Y, and their sinusoidal E_{AY} component. b. PWM pulses between terminals B and Y, and their sinusoidal E_{BY} component.**

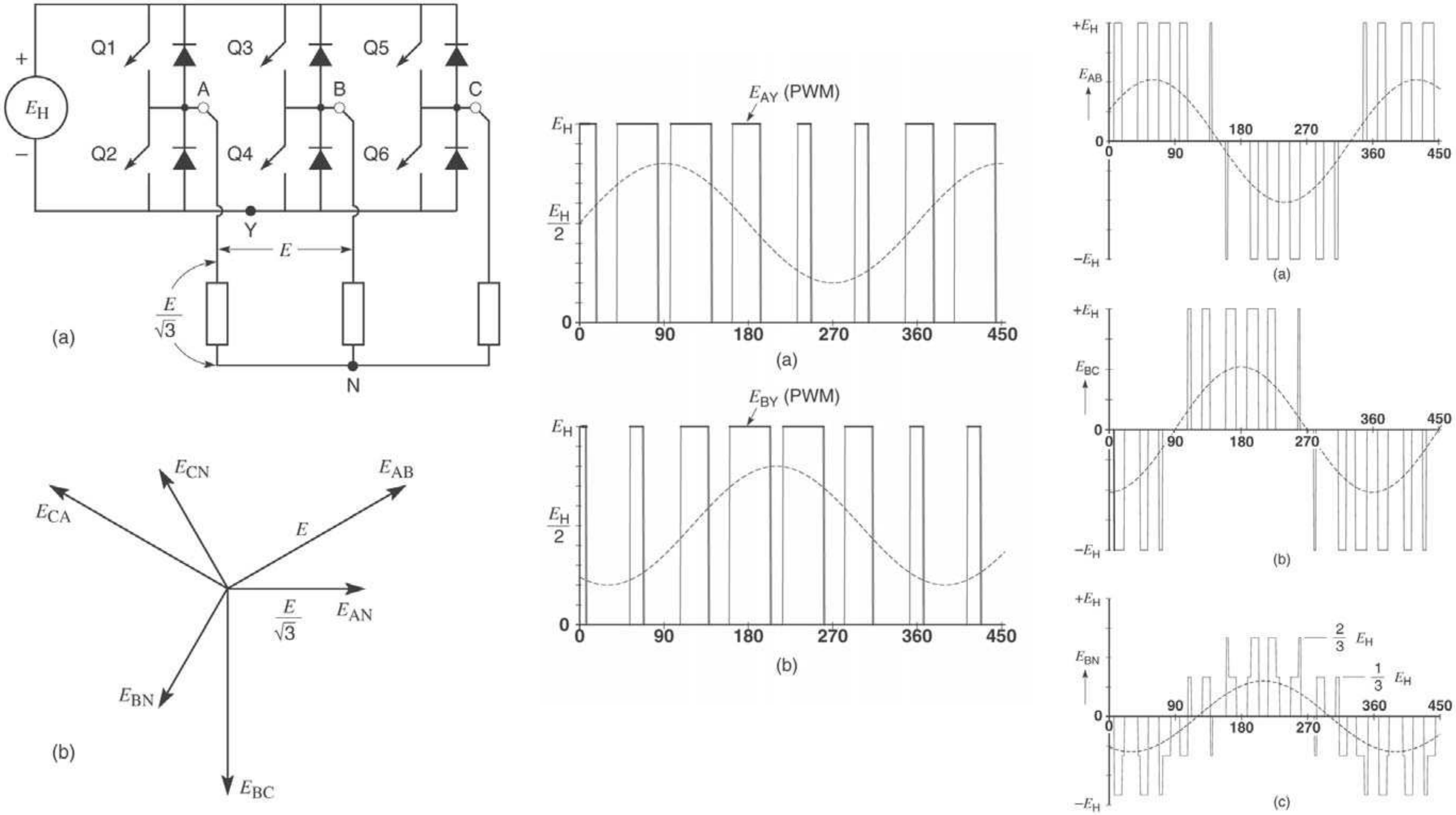
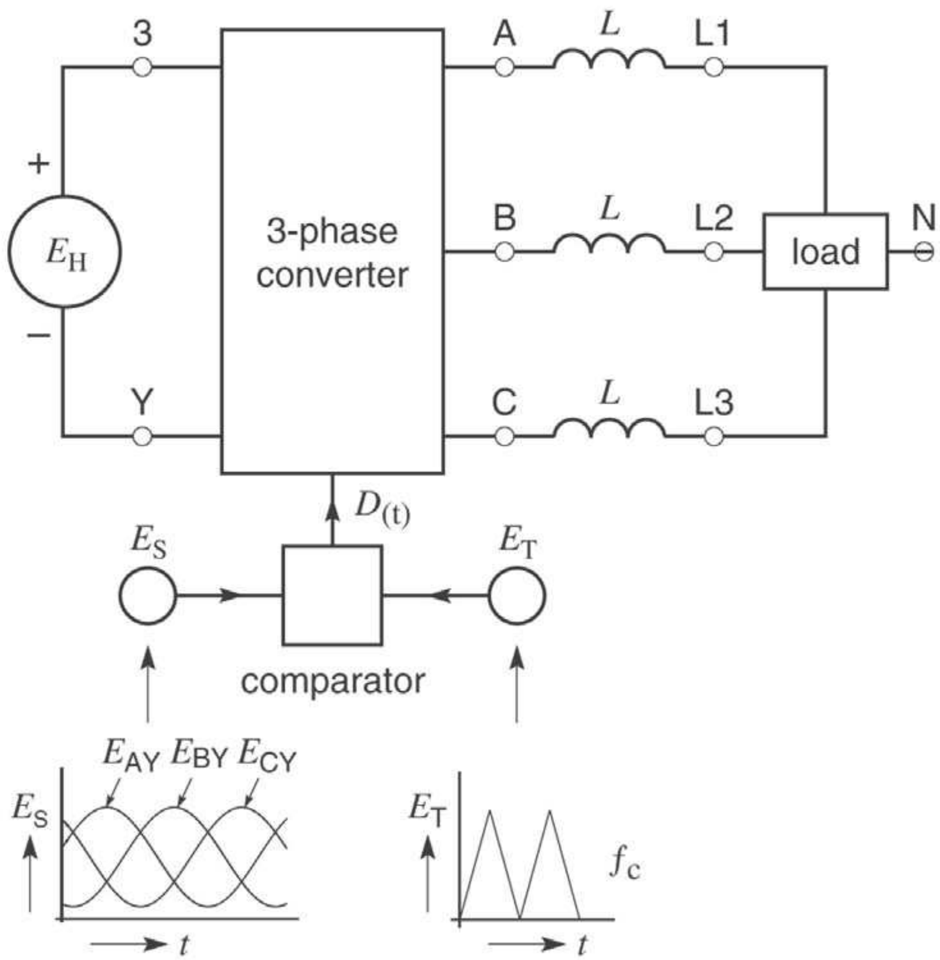


Figure 21.93 **Block diagram of a 3-phase PWM converter.**



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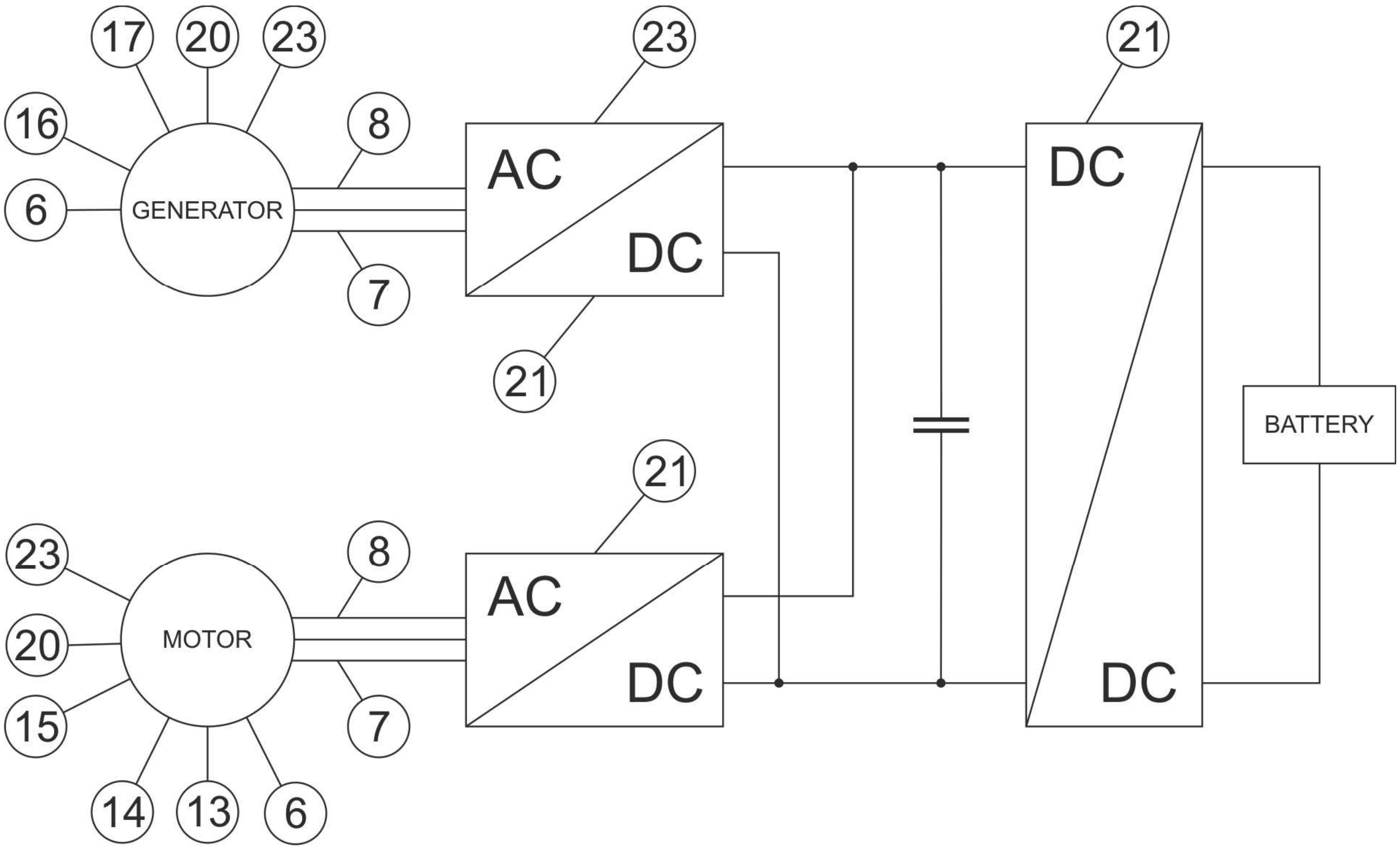
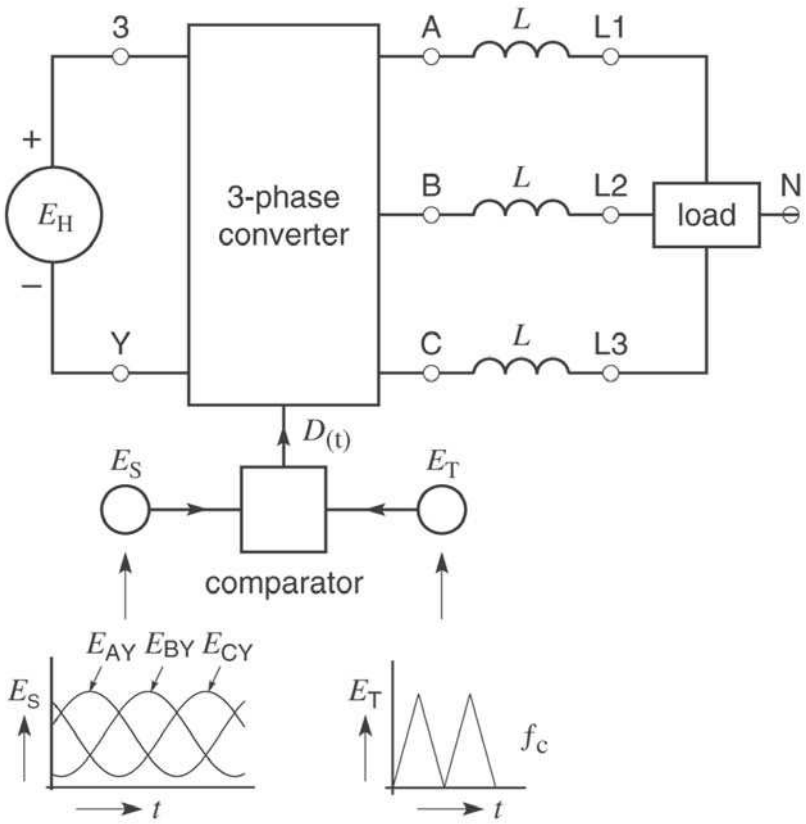

17
20
23
16
6
GENERATOR
8
7
AC
DC
23
21
21
DC
DC
BATTERY
21
23
20
15
14
13
6
MOTOR
8
7
AC
DC

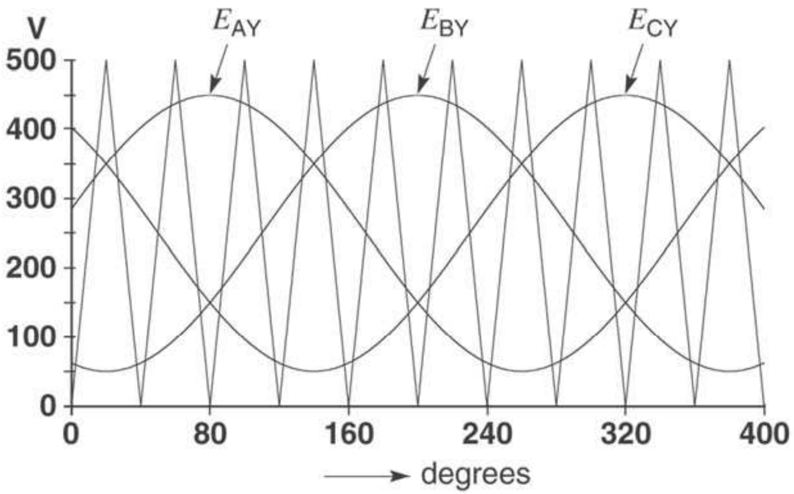
Example 21.15

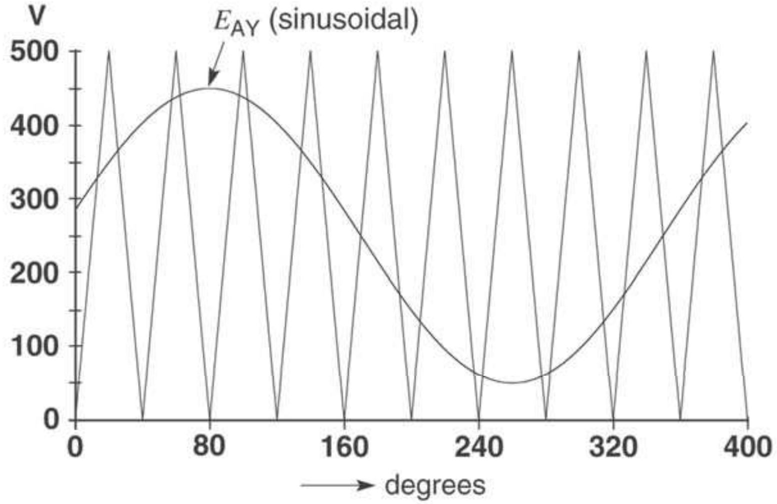
- 3 phase 245 V 60 Hz wanted, dc = 500 V , fc=540 Hz



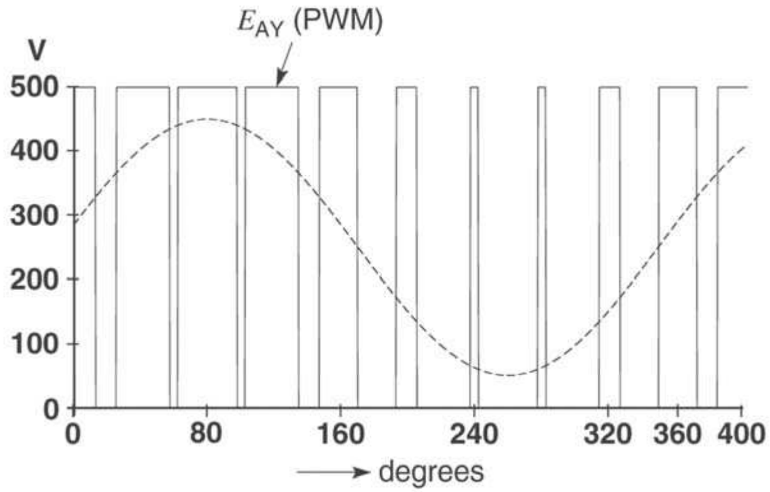
- the peak value of fundamental voltage
- L1 N
- $E_{LN} = 245/\ sqrt(3) = 141$ V
- $E_m = E_{LN}$ sqrt (2) = 200 V

Figure 21.95 **See Example 21-15.**





(a)



(b)

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Figure 21.94 **A more detailed diagram of a 3-phase PWM converter using IGBTs and a 3-phase *RLC* filter to suppress the carrier frequency components. The capacitors across the dc side provide a path for the reactive currents that are drawn by the 3-phase load.**

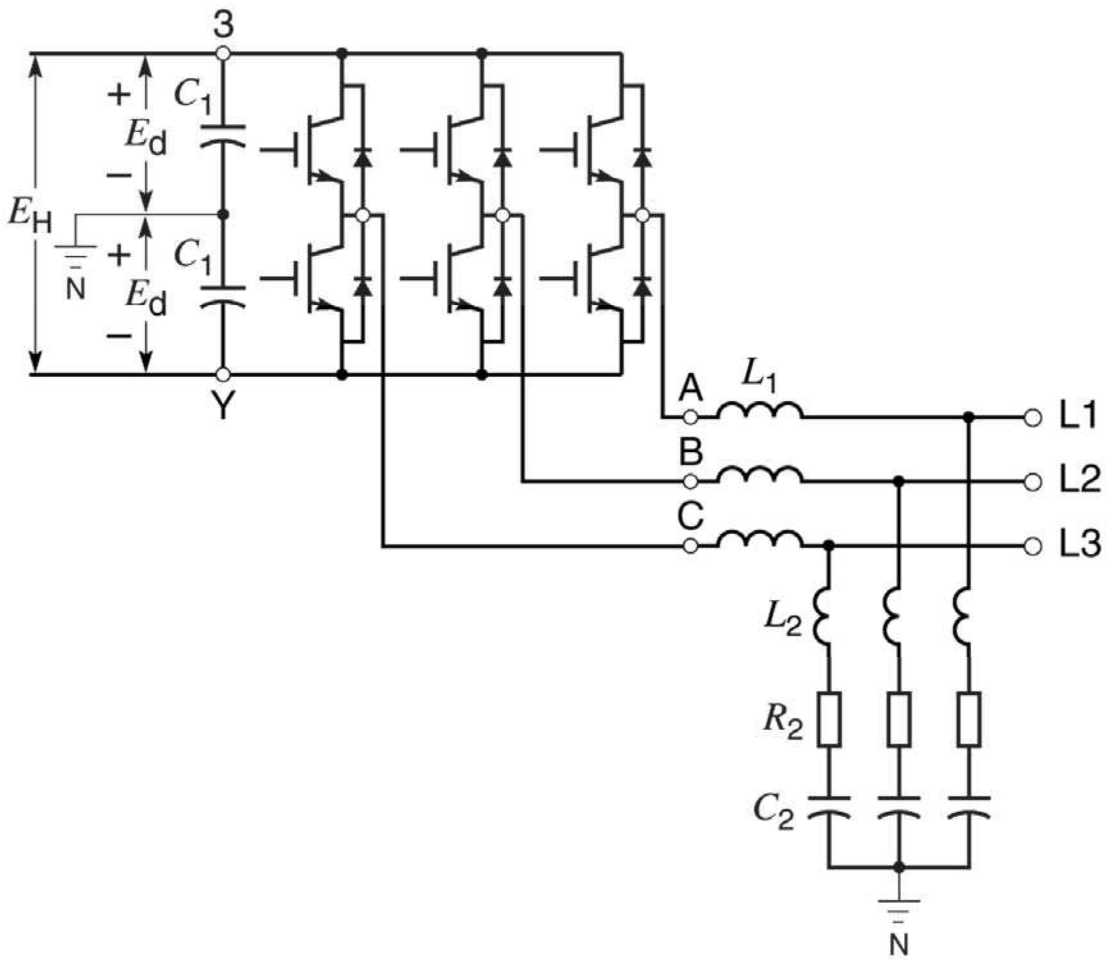
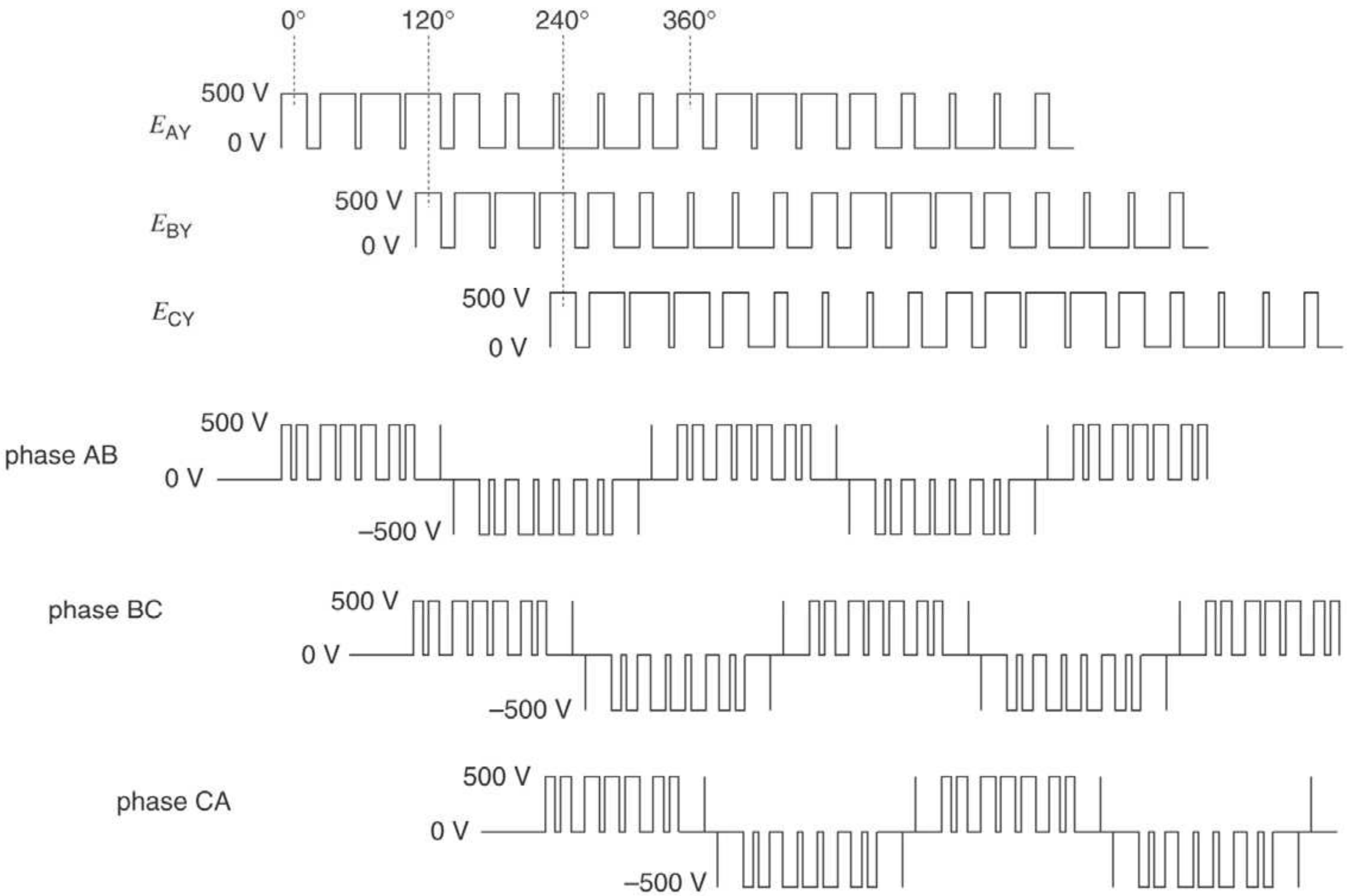
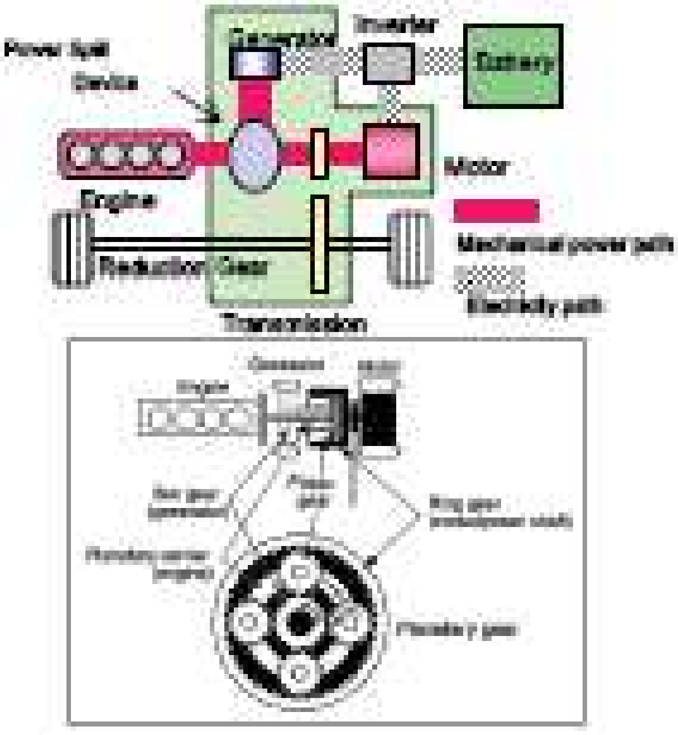
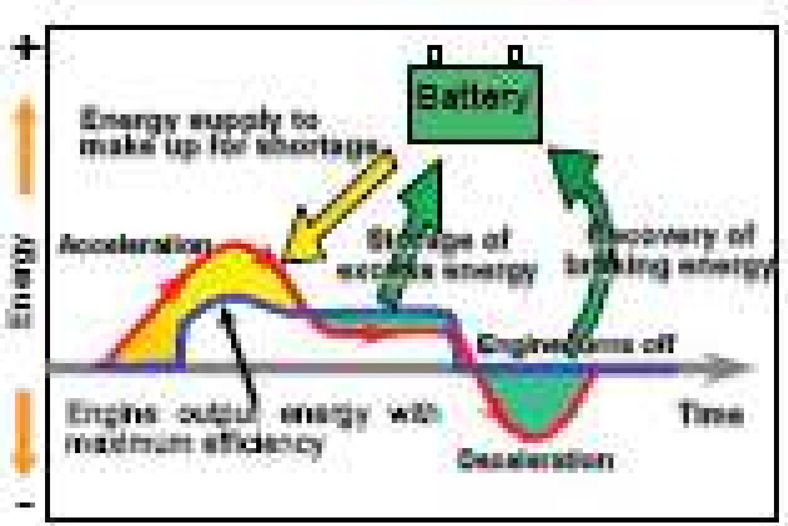


Figure 21.97 **Three-phase PWM voltages produced by a dc-to-ac converter operating at a carrier frequency of 540 Hz with a 500 V dc input. Top: E_{AY}, E_{BY}, E_{CY} outputs, peak sinusoidal component = 200 V. Bottom: E_{AB}, E_{BC}, E_{CA} outputs, peak 60 Hz sinusoidal component = 346 V, RMS value = 245 V.**

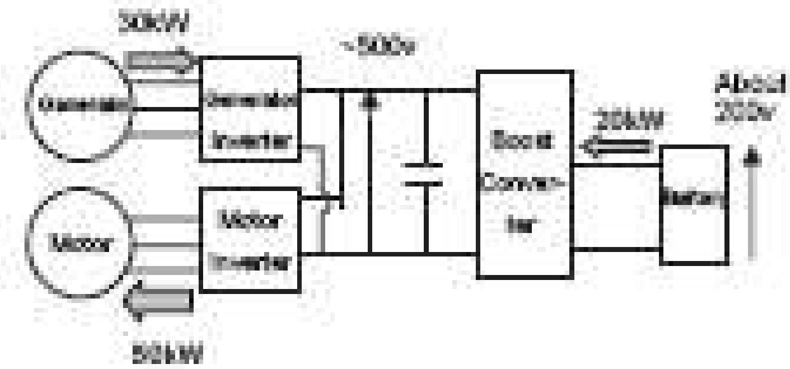


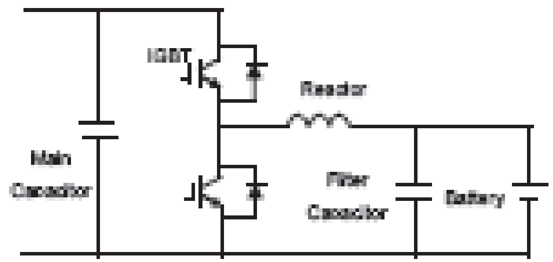
Energy management

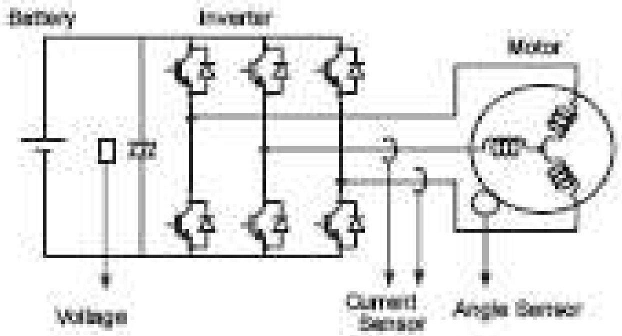




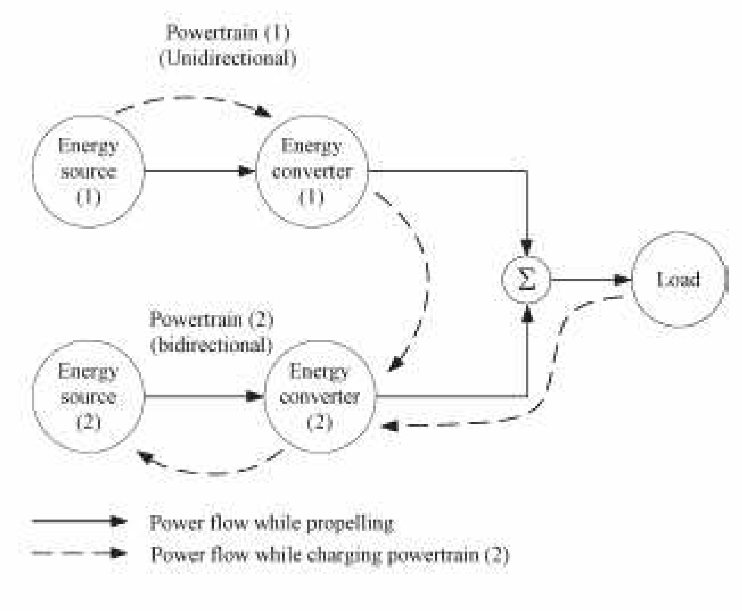
Variable voltage system

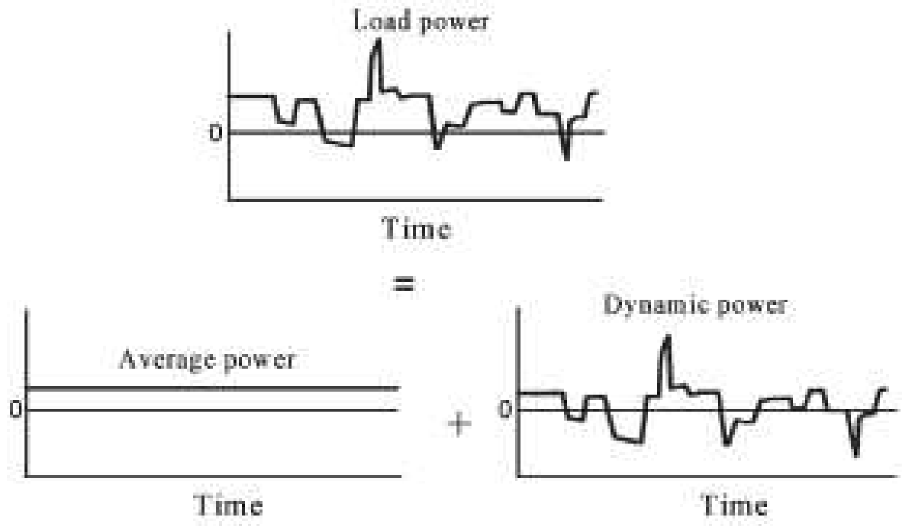






TUDelft


Powertrain (1)
(Unidirectional)
Energy source (1)
Energy converter (1)
Σ
Load
Powertrain (2)
(bidirectional)
Energy source (2)
Energy converter (2)
Power flow while propelling
Power flow while charging powertrain (2)


Load power
0
Time
=
Average power
0
Time
+
Dynamic power
0
Time

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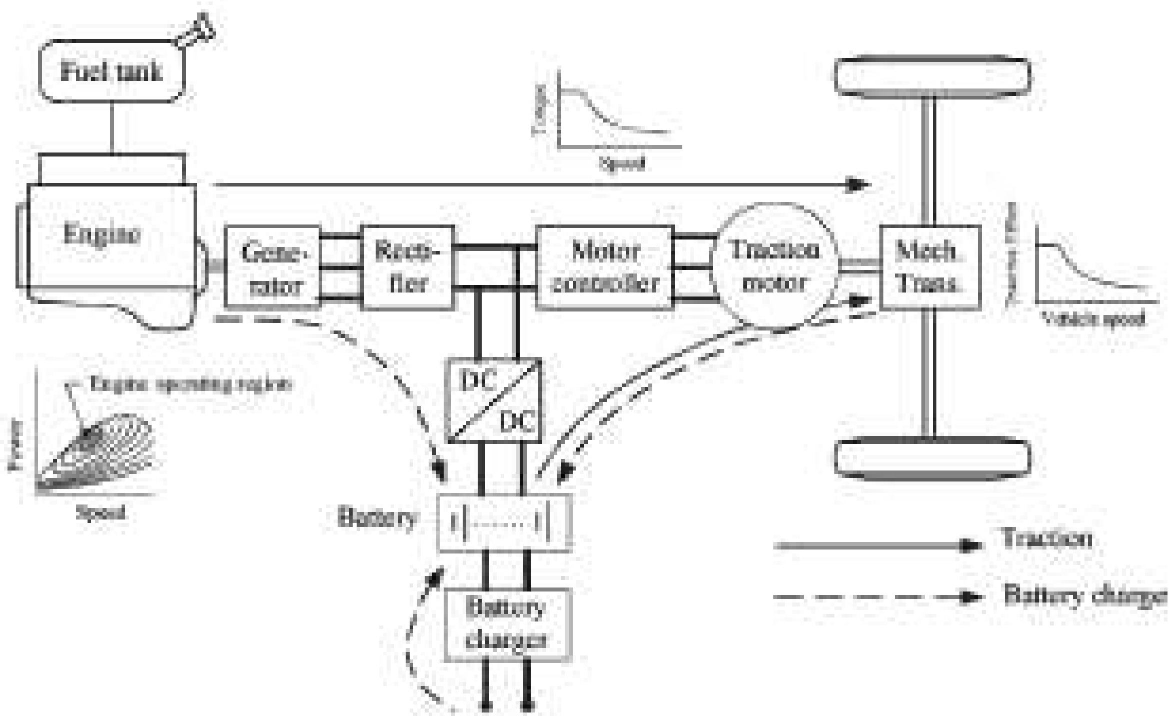
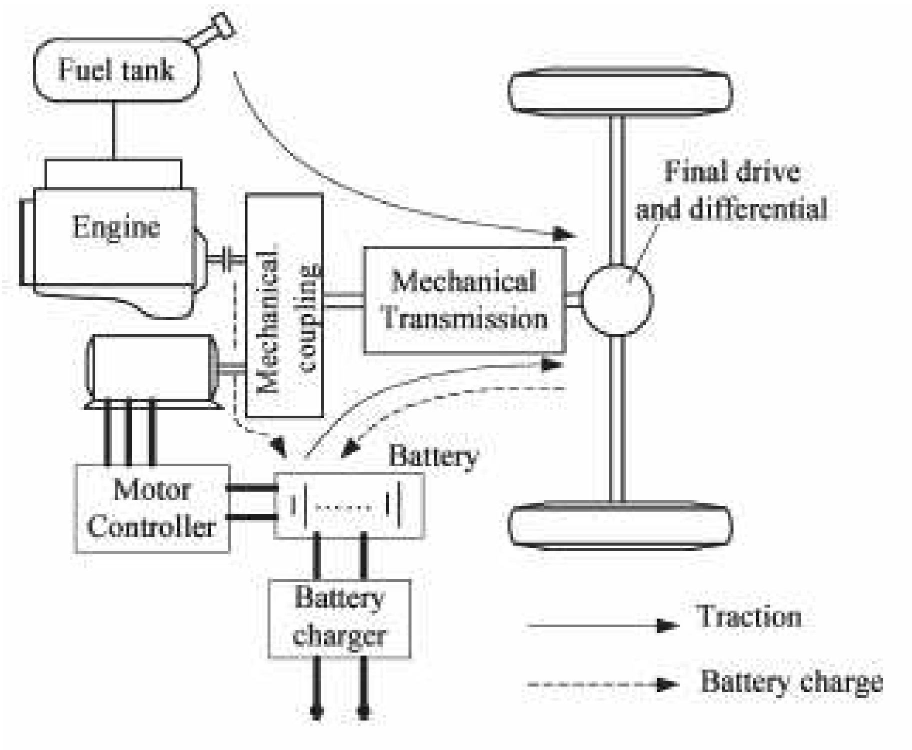
Series hybrid drivetrain



TUDelft

Parallel hybrid drivetrain



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Energy storage

can be classified as

- **Mechanical Energy Storage.**
- **Magnetic Energy Storage.**
- **Thermal Energy Storage.**
- **Chemical Energy Storage.**

Energy storage device

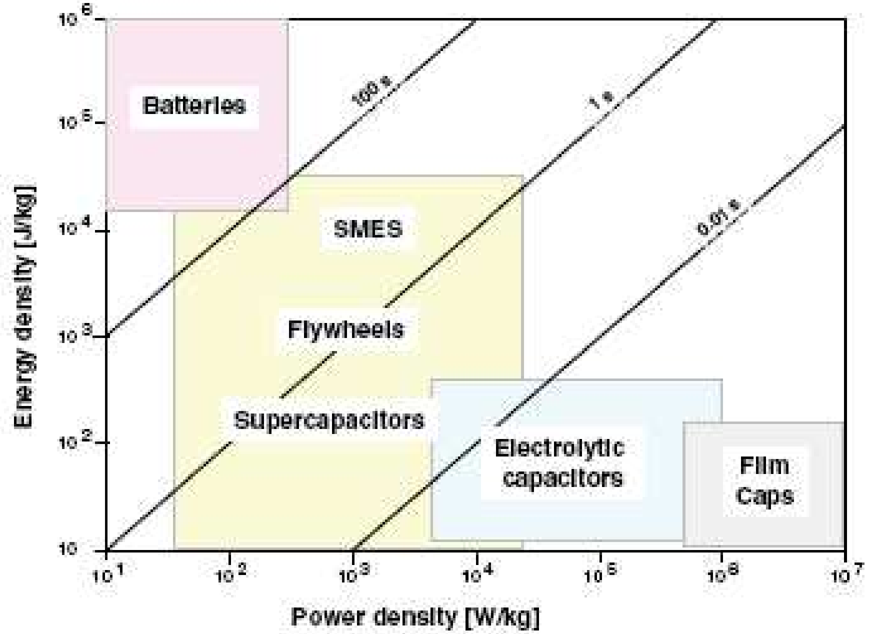
Fundamental properties

- **the energy that can be stored in the element;**
- **the power that can be drawn from/charged in the storage element;**
- **the specific energy (energy per unit weight);**
- **the specific power (power per unit weight);**
- **the energy density (energy per unit volume);**
- **the power density (power per unit volume).**

Energy storage device

Technology and economy

- cycle life;
- self-discharge;
- costs
- fast charge time;
- cell voltage;
- load current;
- maintenance requirement;
- energy efficiency.

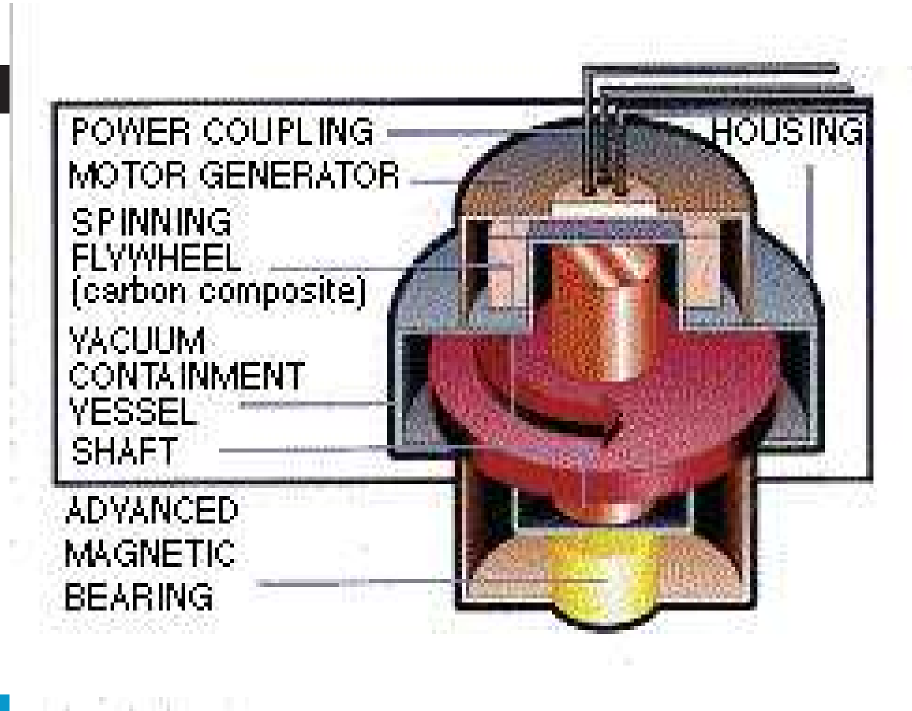

Batteries
SMES
Flywheels
Supercapacitors
Electrolytic capacitors
Film Caps
100 s
1 s
0.01 s
Energy density [J/kg]
Power density [W/kg]

TUDelft

Mechanical Energy Storage: Fly Wheels

- **Principle: Energy is stored in the form of Mechanical Energy.**
- **Light weight fiber com[...] to increase efficiency.**
- **Energy density**

  =0.05MJ/Kg, η=0.8



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•**The Energy Density is defined as the Energy per unit mass:**

$$\frac{E}{m} = \frac{1}{2}V^2 = \frac{\sigma}{\rho}$$

•**Where,**

V is the circular velocity of the flywheel
σ is the specific strength of a material
ρ is the density of the material

•

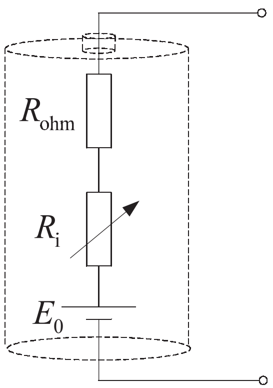
Properties of some materials used for building flywheels.

Materials	Density, ρ(Kg/m3)	Specific strength, σ(MNm/Kg)
Steel	7800	0.22
Aluminium alloy	2700	0.22
Titanium	4500	0.27
Glass £bre reinforced polymer	2000	0.80
Carbon £bre reinforced polymer	1500	1.60

Advantages and disadvantages:

- Very compact when compared to other energy storage systems.
- Flywheels are used for starting and braking locomotives.
- A flywheel is preferred due to light weight and high energy capacity.
- It is not economical as it had a limited amount of charge/discharge cycle.

Batteries

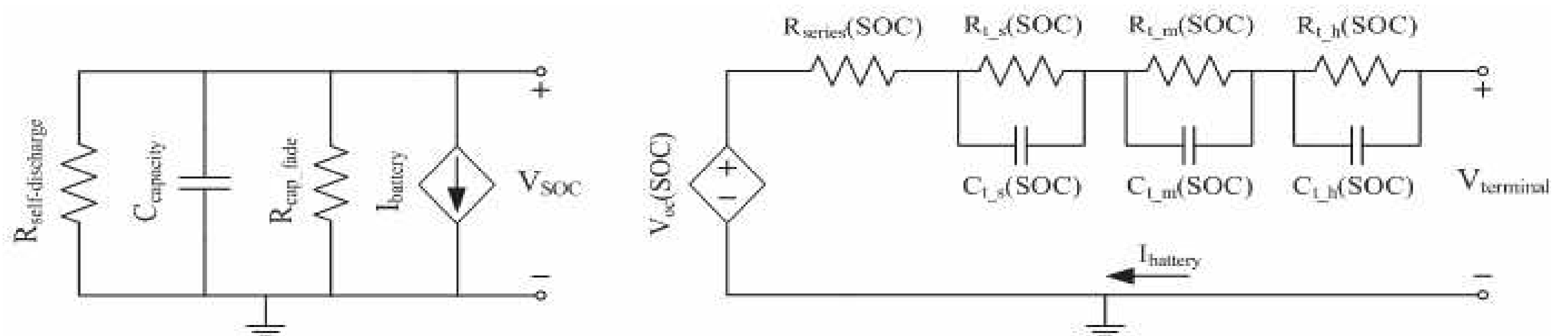


$$P_{peak,storage} = \frac{E_0^{\ 2}}{4(R_{int} + R_{ohm})}$$

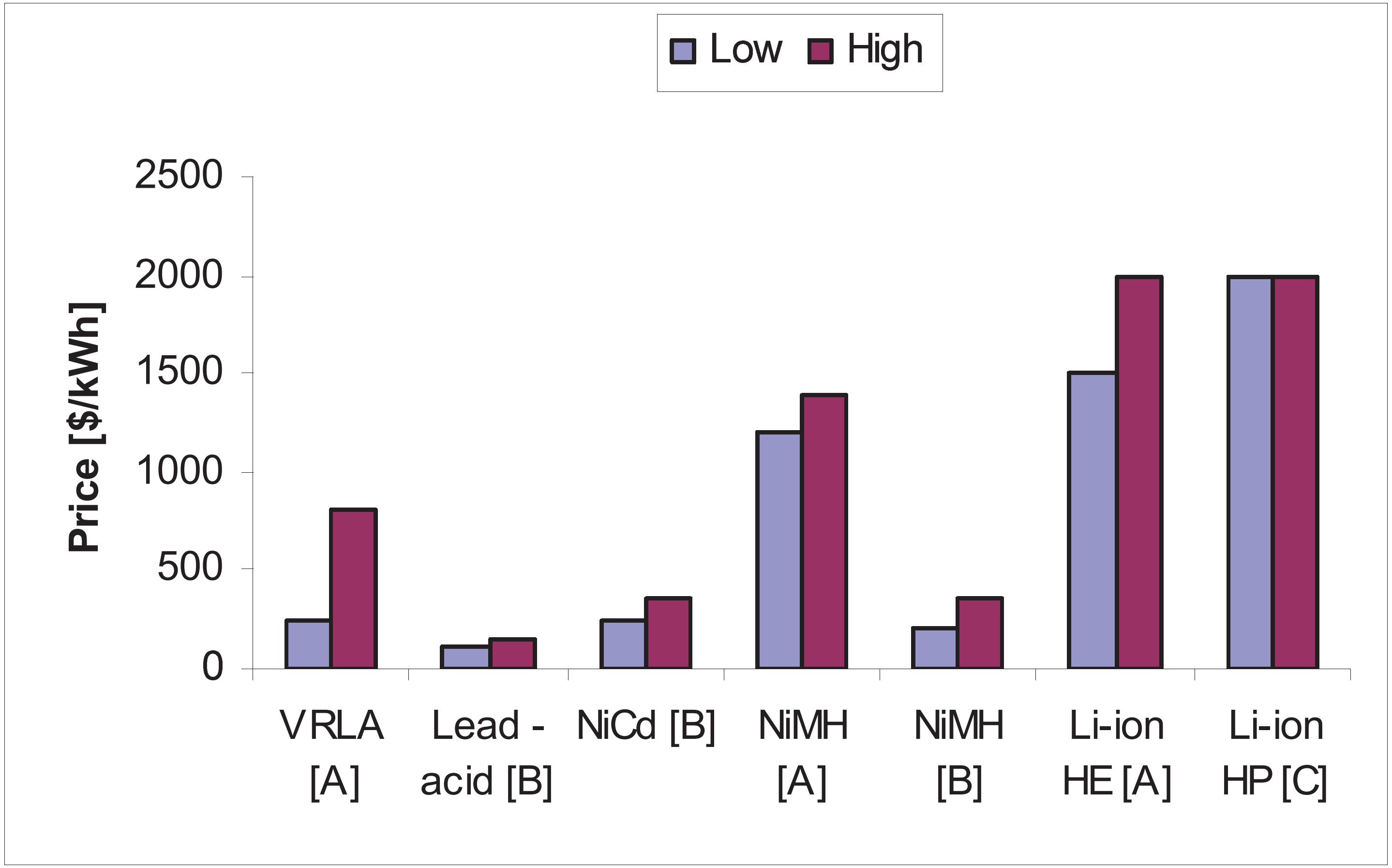
$$P^{peak,storage}_{/gram} = \frac{P_{peak,storage}}{m}$$

- **the lead-acid battery, nickel cadmium battery (NiCd), the nickel metal hydride battery (NiMH) and the Lithium ion battery (Li-ion).**

Battery model

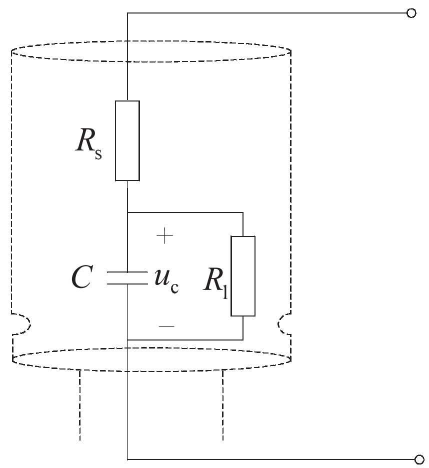


Comparison of prices



TUDelft

Supercapacitor



$$E = \tfrac{1}{2} C {u_C}^2$$

$$P_{\text{peak,storage}} = \frac{{u_c}^2}{4(R_s)}$$

TUDelft

		Energy Density [Wh/l]	Specific Energy [Wh/kg]	Specific Power [W/kg]		Cycle life	Calendar life [years]	Self-discharge [%/month]	Efficiency [%]		Cell Voltage [V]				Load Current [C]		Power Density	Internal Resistance [mΩ]	Fast Charge Time [h]	Operating Temperature [°C]	Overcharge Tolerance	Maintenance Requirement	Safety	Toxicity	Discharge profile (relatively)
				peak	continuous				Charging	Overall	Nominal	Open Circuit	Operating	End of Life	Peak	Best Result									
Lead-acid	Sealed	-	30-50	-	-	200-300[1] [2] [37]	-	5[3]	-	-	2	-	-	-	5[4]	0,2	-	< 100[5] [6]	8 to 16	-20 to 60[7]	high	3 to 6 months	thermally stable	lead and acids environmentally unfriendly	-
	Traction	80[35]	25[35]	-	-	1500[26] [8]	6	4-6[9] [10]	-	-	2,0	2,1	2,0-1,8	1,75	-	-	moderately high	-	-	-20 to 40	-	-	-	-	flat
	VRLA	-	10-20	-	50-100	1000[33]	5	Very low	75-95	-	-	-	-	-	-	-	-	-	-	10 to 30	-	1 check/year	-	high environmental impact	-
		-	35-50	150-400	-	500-1000	-	9,1[11]	-	> 80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NiCd		-	45-80	-	-	1500[27] [12]	-	20[28] [13]	-	-	1,25[14]	-	-	-	20	1	-	100-200[30] [15]	1[16]	-40 to 60[32]	moderate	30 to 60 days	thermally stable, fuse recommended	Highly toxic, environmentally unfriendly	-
	Vented Pocket plate	40[35]	20[35]	-	-	500-2000[26 33]	8-25	5[34 35]	-	-	1,2	1,29	1,25-1,00	1,0	-	-	high	-	-	-20 to 45	-	-	-	-	flat
	Vented Sintered plate	58-96[35]	30-37[35]	-	-	500-2000[26 33]	3-10	10[34 35]	-	-	1,2	1,29	1,25-1,00	1,0	-	-	high	-	-	-40 to 50	-	-	-	-	very flat
	Sealed	100[35]	35[35]	-	-	300-700[26 33]	2-5	15-20[34 35]	-	-	1,2	1,29	1,25-1,00	1,0	-	-	moderate to high	-	-	-40 to 45	-	-	-	-	very flat
		-	50-60	80-150	-	800	-	15,2[36]	-	75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NiMH		-	60-120	-	-	300 to 500[26 27 37]	-	30[28 38]	-	-	1,25[39]	-	-	-	5	≤ 0,5	-	200 to 300[30 40]	2 to 4	-20 to 60[32]	low	60 to 90 days	thermally stable, fuse recommended	relatively low toxicity but should be recycled	-
		240[35]	75[35]	-	-	300-600[26 33]	2-5	15-25[34 35]	-	-	1,2	1,4	1,25-1,10	1,0	-	-	moderate to high	-	-	-20 to 50	-	-	-	-	flat
		-	40-80	-	200-600	800-1200[33]	10	Moderate	65-70	-	-	-	-	-	-	-	-	-	-	-20 to 40	-	moderate	-	low environmental impact	-
		-	70-95	200-300	-	750-1200+	-	91,3[36] [17]	-	70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

		Energy Density [Wh/l]	Specific Energy [Wh/kg]	Specific Power [W/kg]		Cycle life	Calendar life [years]	Self-discharge [%/month]	Efficiency [%]		Cell Voltage [V]				Load Current [C]		Power Density	Internal Resistance [mΩ]	Fast Charge Time [h]	Operating Temperature [°C]	Overcharge Tolerance	Maintenance Requirement	Safety	Toxicity	Discharge-profile (relatively)
				peak	continuous				Charging	Overall	Nominal	Open Circuit	Operating	End of Life	Peak	Best Result									
Li-ion	**HE (cobalt)**			-	-	300-500[26 27]	-	10[28 45]	-	-	3,6[1]		-	-	< 3	≤ 1	-	150-300[30] [2]	1,5 to 3	-20 to 60[32]	low, no trickle charge	not required	protection circuit required; stable to 150 °C	low	-
	HE (cobalt)	400[35]	150[35]	-	-	>10 000[26 33]	-	2[34 35]	-	-	4,0	4,1	4,0-3,0	3,0	-	-	moderate; high in prismatic designs	-	-	-20 to 50	-	-		-	sloping
	HE	-	60-100	-	200-1000	> 1000[33]	10	Moderate	90-95	-	-	-	-	-	-	-	-	-	-	-20 to 45	-	moderate	-	low environmental impact	-
	HE	-	80-130	200-300	-	≥ 1000	-	10,6[36]	-	> 95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	HP (manganese)	-	100-135	-	-	better than 300-500[26 27]	-	10[28] [3]	-	-	3,6[43]	-	-	-	> 30	≤ 10	-	25-75[30] [4]	≤ 1	-20 to 60[32]	low, no trickle charge	not required	protection circuit recommended; stable to 250 °C	low	-
	HP (phosphate)	-	90-120	-	-	> 1000[27] [5]	-	10[28 45]	-	-	3,3	-	-	-	> 30	≤ 10	-	25-50[30 46]	≤ 1	-20 to 60[32]	low, no trickle charge	not required	protection circuit recommended; stable to 150 °C	low	-
	HP (infoepyon)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Supercapacitor		-	1 – 3	-	500 – 2000	> 500.000	> 10	Low	85 – 95	-	-	-	-	-	-	-	-	-	-	-25 to 65	-	no	-	low environmental impact	-

age voltage under load is 3.7 V, so higher than the nominal voltage. The battery is often rated to this average voltage.
pack.
internal protection circuit uses 3 % of the stored energy per month.
cell.
conditions.

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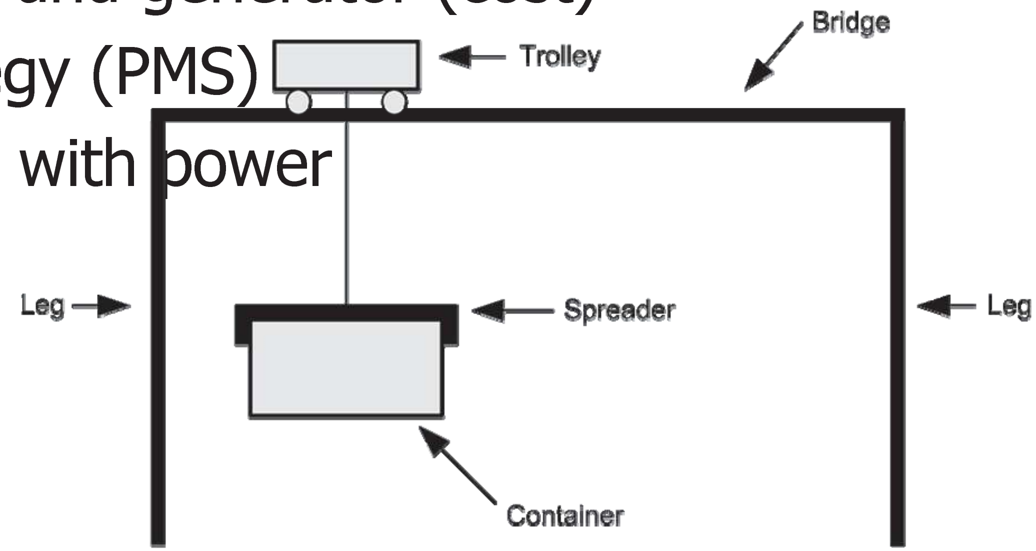
Case study

Stand alone systems with diesel generator and 4Q operation

(crane, elevator, car)

- Size of the energy storage and generator (cost)
- Power Management Strategy (PMS)
- voltage level and interface with power electronic converter



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Hybrid Dynamic Systems with Energy Storage

Stand alone systems with diesel generator and 4Q operation
(crane, elevator, car)

- Size of the energy storage and generator (cost)
- Power Management Strategy
- voltage level and interface with power electronic converter

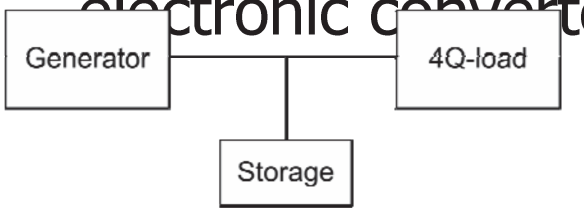

Fig. 1. Overview of generator with energy storage for 4Q-load.

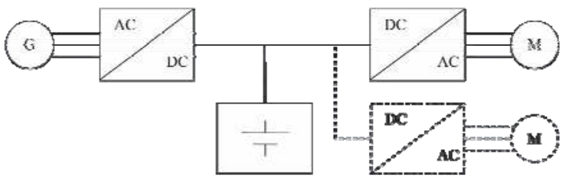

Fig. 2. System topology for generator with Li-ion HP battery.

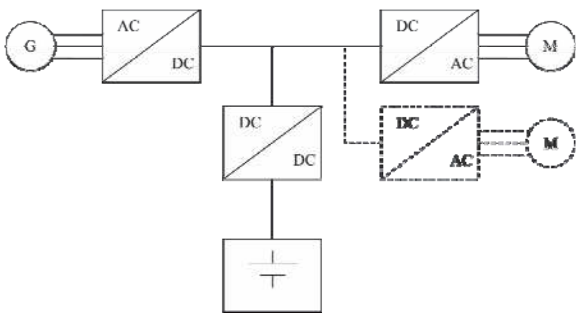

Fig. 3. System topology for generator with Super capacitor.

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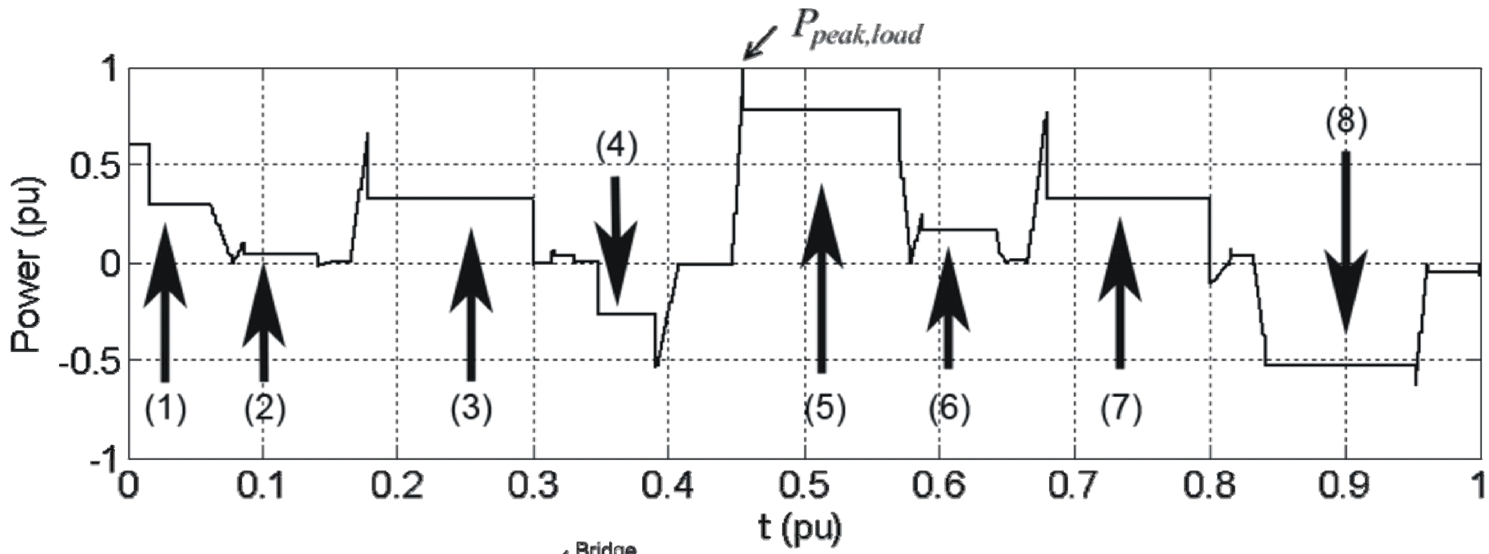
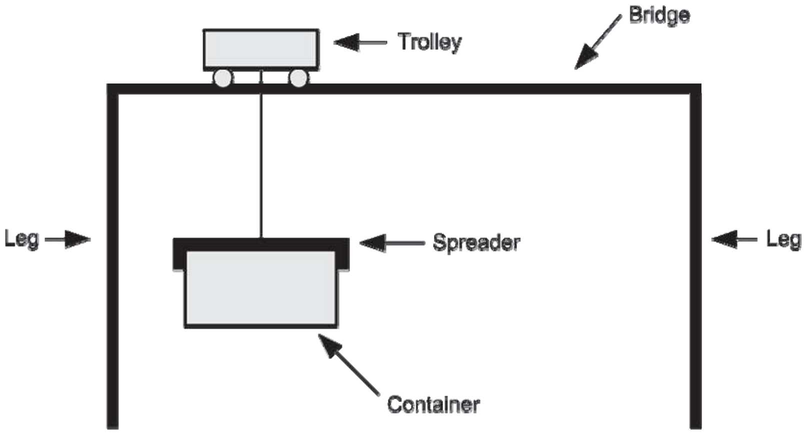
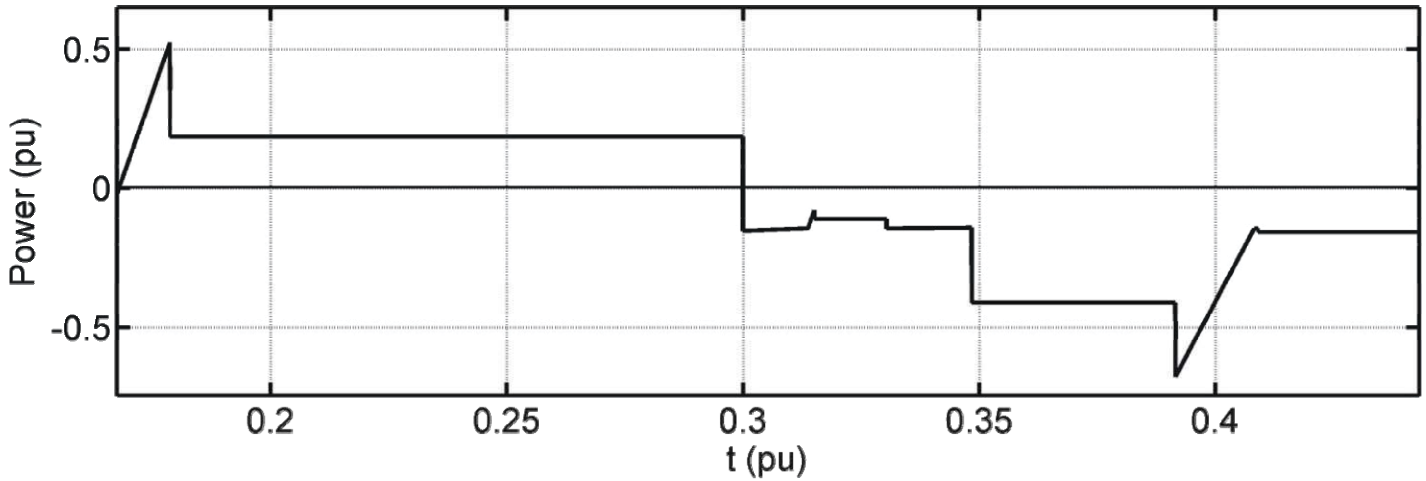
Load profile





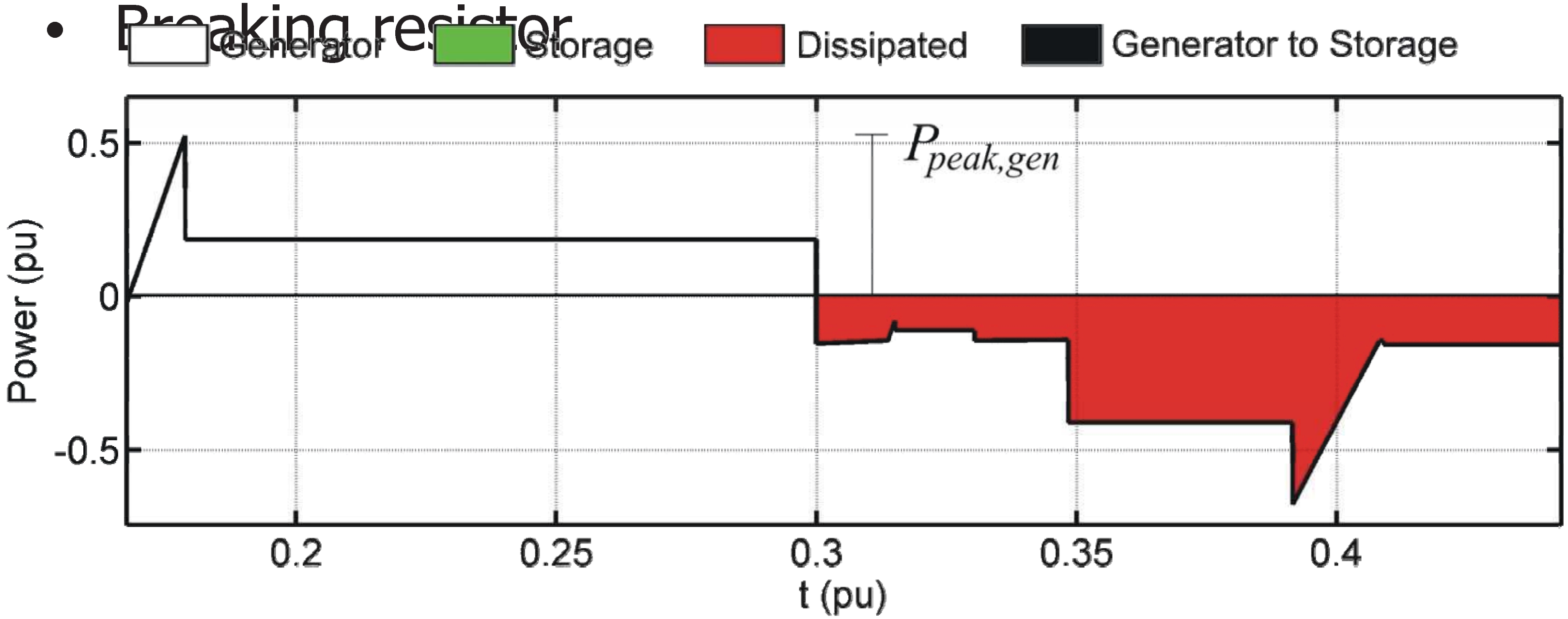
1. hoisting the empty spreader;
2. moving the trolley without load;
3. moving the crane;
4. lowering the spreader without load;
5. hoisting a container;
6. moving the trolley with a container;
7. moving the crane with a container;
8. lowering the container.

Simplified power profile



Only Generator

- Max 1 pu, average power 0,14 pu
- Breaking resistor



Dia 114

PB1 The first part of the graph shows the elevator accelerating to travel up, travels up for a while at constant speed and decelerates. In the second part of the graph the elevator accelerates to travel down, travels down for a while at constant speed, and decelerates. There is a need for a large peak power for a short period during acceleration, and that during deceleration the system supplies small peak energy back during a short period.
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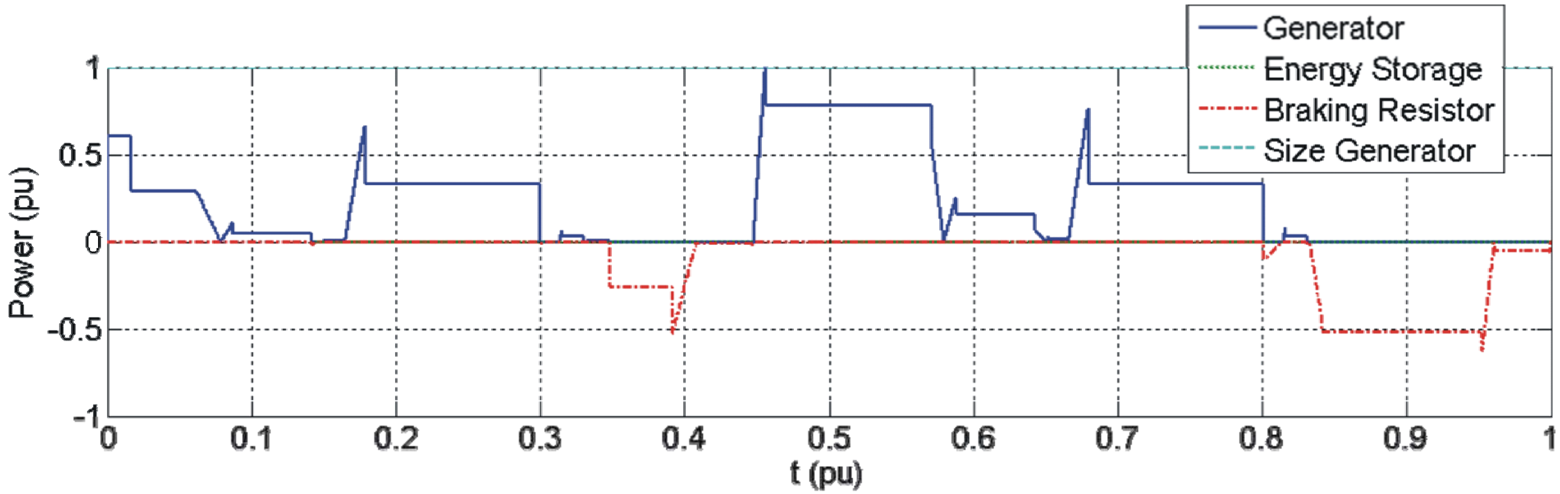
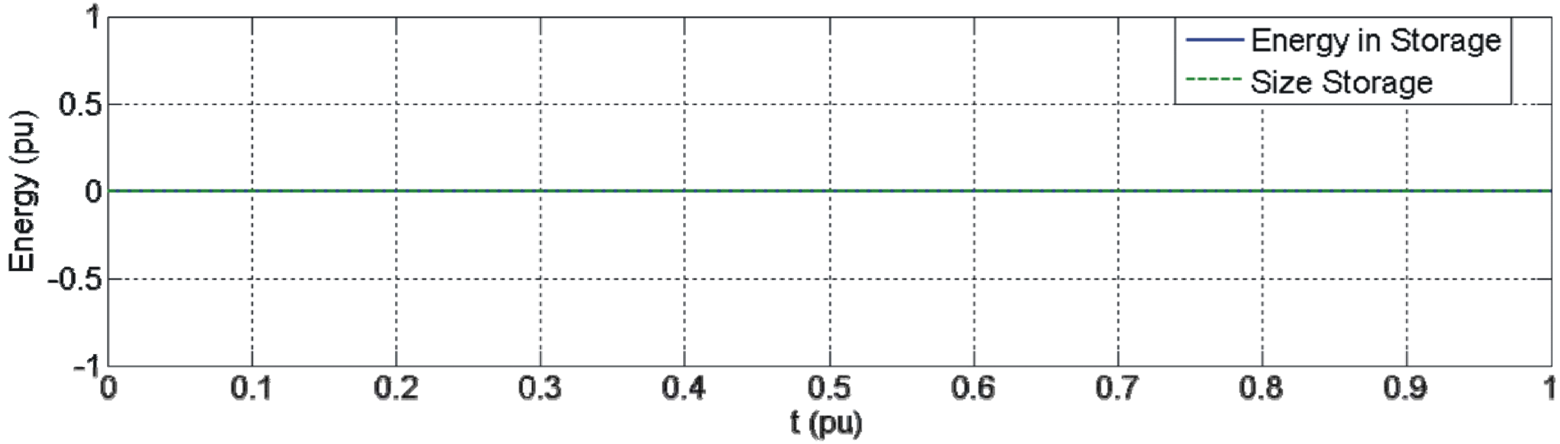
PB2 the power is fully being supplied by a generator. This system shows no difference with the normal case and is used as a reference.

The nominal peak power of the generator is
P Bauer; 27-5-2008

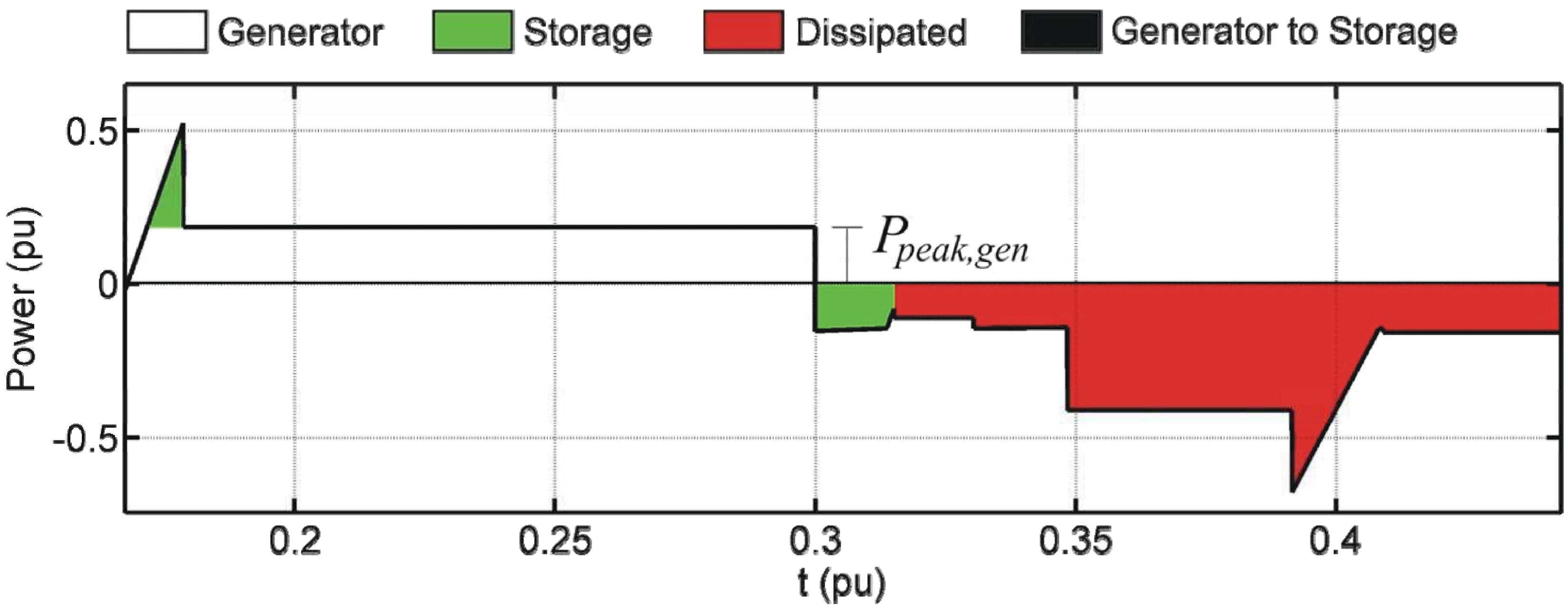
Only Generator





Peak power shaving

- Generator Max power 0,78 pu, 0,021 pu stored



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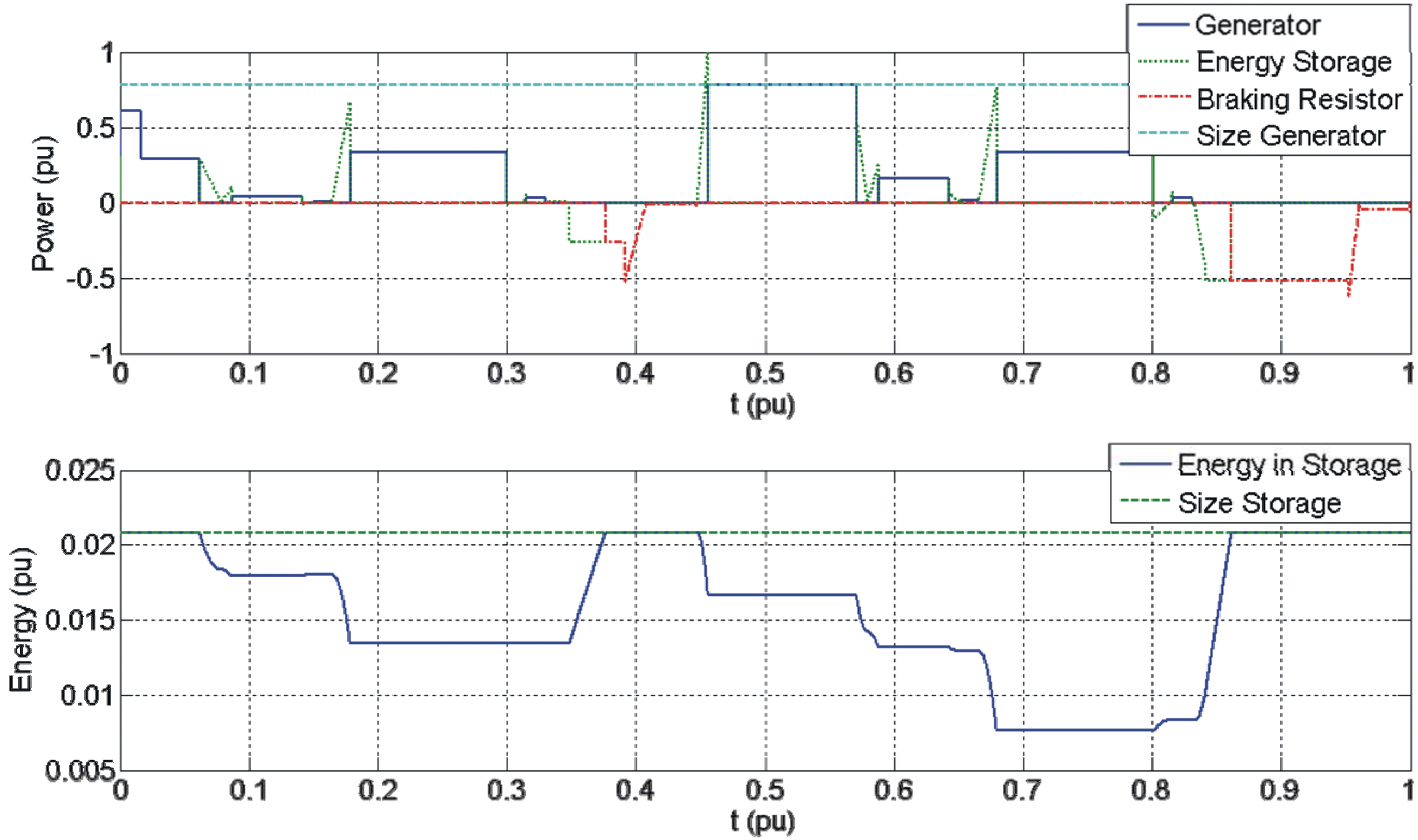
Dia 116

PB3 When the Peak Power Shaving PMS is used, the generator supplies most of the power. The storage element only supplies the power peaks needed for a short period of time. Parts of more or less constant power are supplied by the generator.T he storage element will be small. Not all regenerated energy can be stored in the storage element because of this small size.The nominal peak power of the generator is 0,78 . The energy that should be stored in the storage element is

P Bauer; 27-5-2008

Peak power shaving



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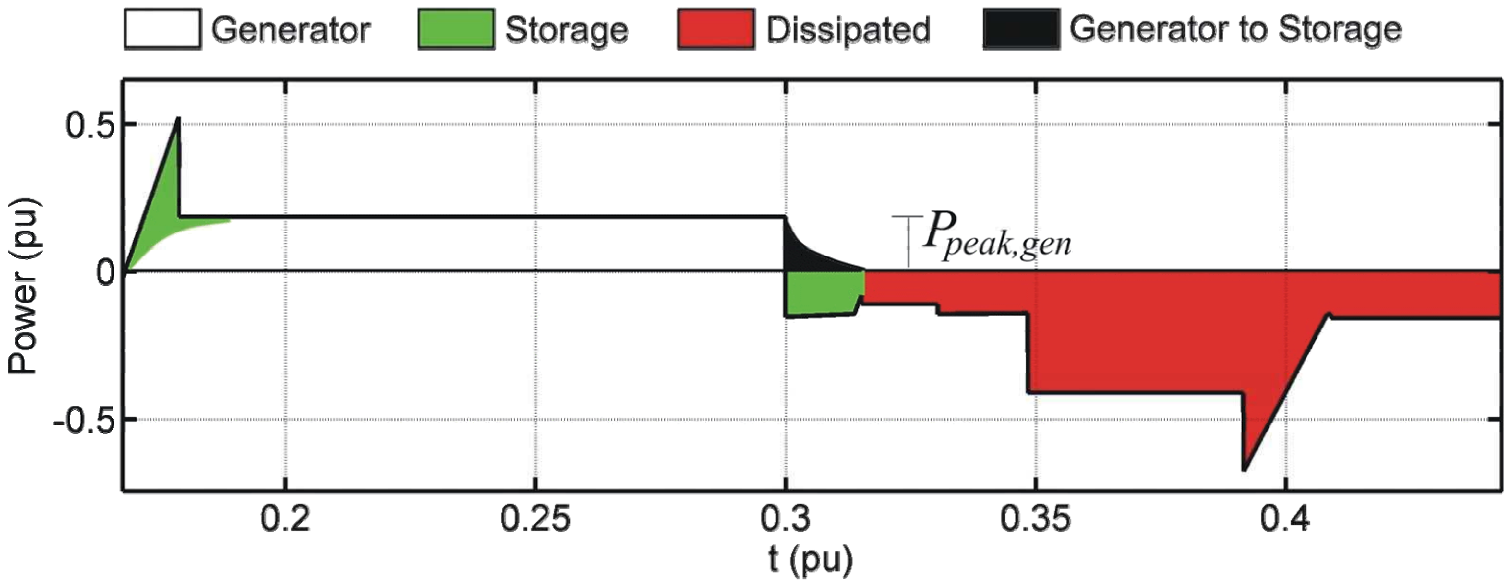
Dynamic Power Management



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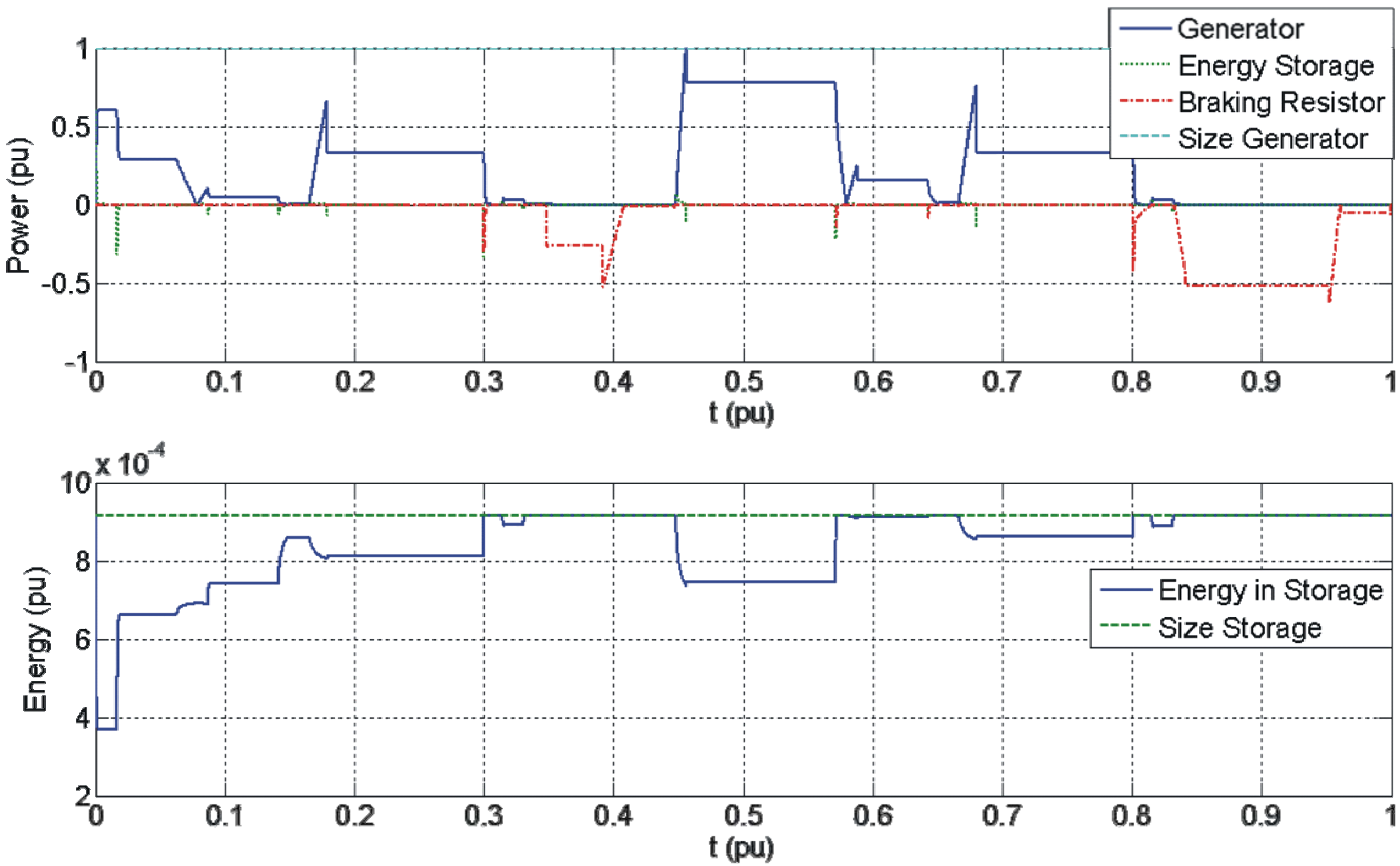
Dia 118

PB4 The Dynamic Solution PMS (DS) is specially designed for use with a VSCF generator. Such a generator cannot react to changes in the output power instantaneously. The energy storage is used to supply/absorb the difference in needed power and power from the generator.
P Bauer; 27-5-2008

Dynamic Power Management



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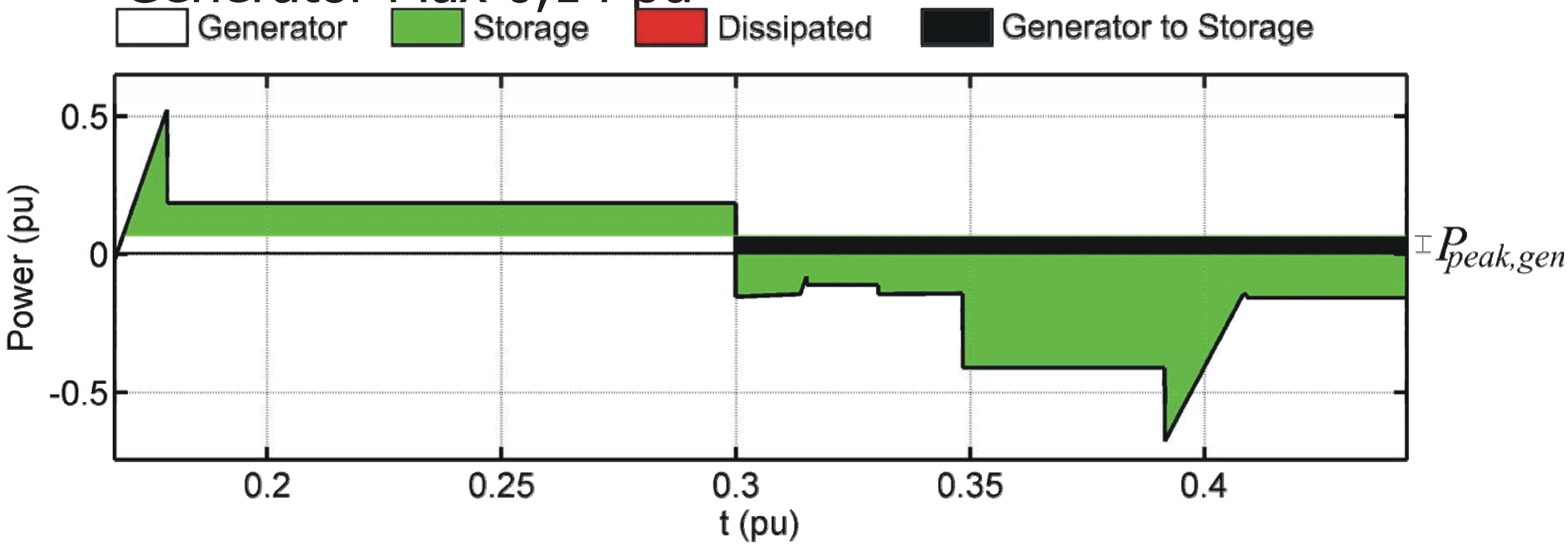
Average power

- Generator Max 0,14 pu



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Dia 120

PB5 In the Average Power PMS (AV), the generator continuously supplies the average power needed. All variations on this average power will be supplied or absorbed by the energy storage.

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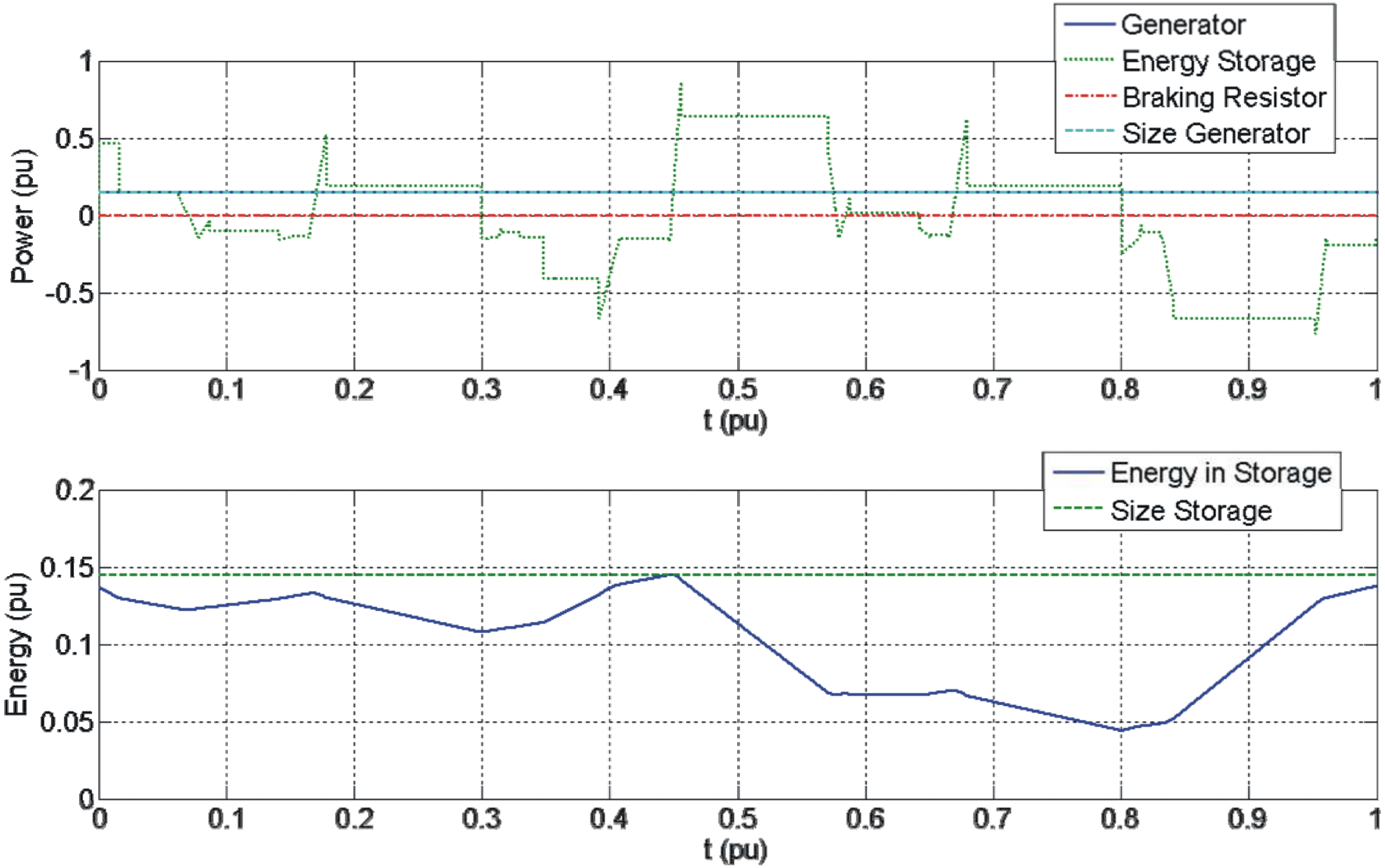
Average power



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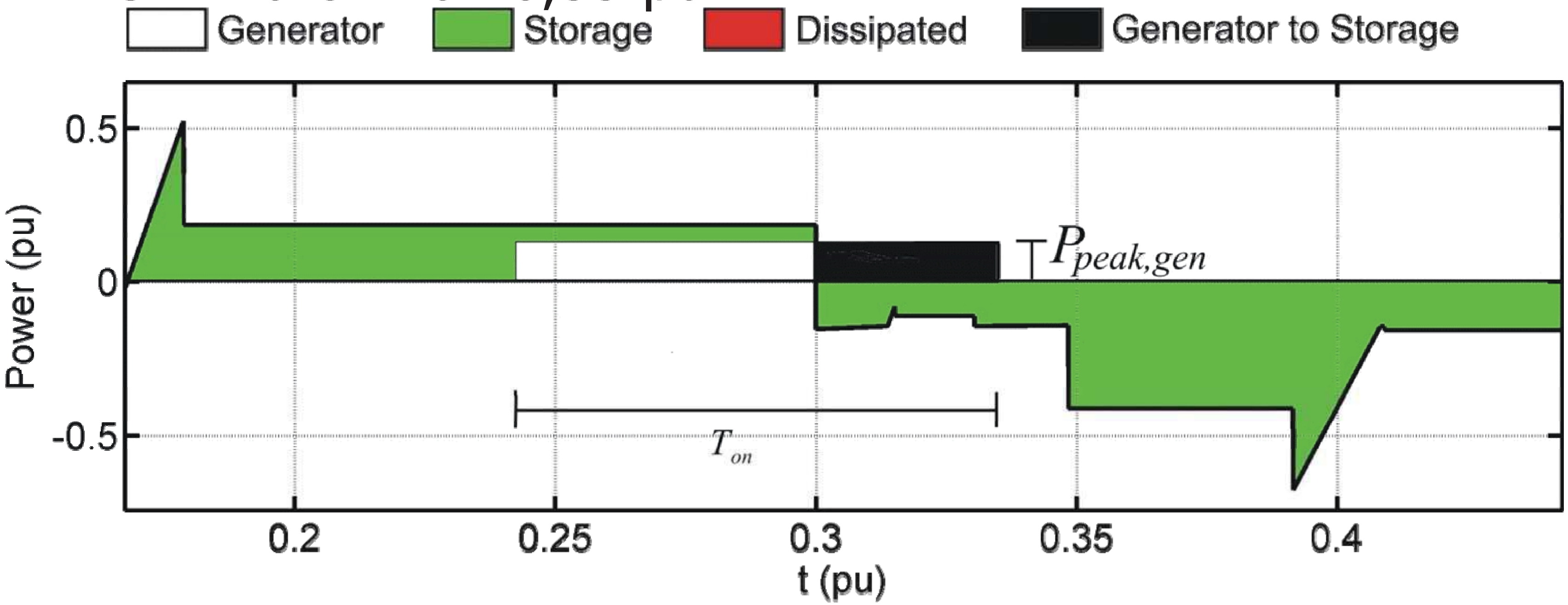
PB7

Max On or Off Power Management

- Generator Max 0,33 pu



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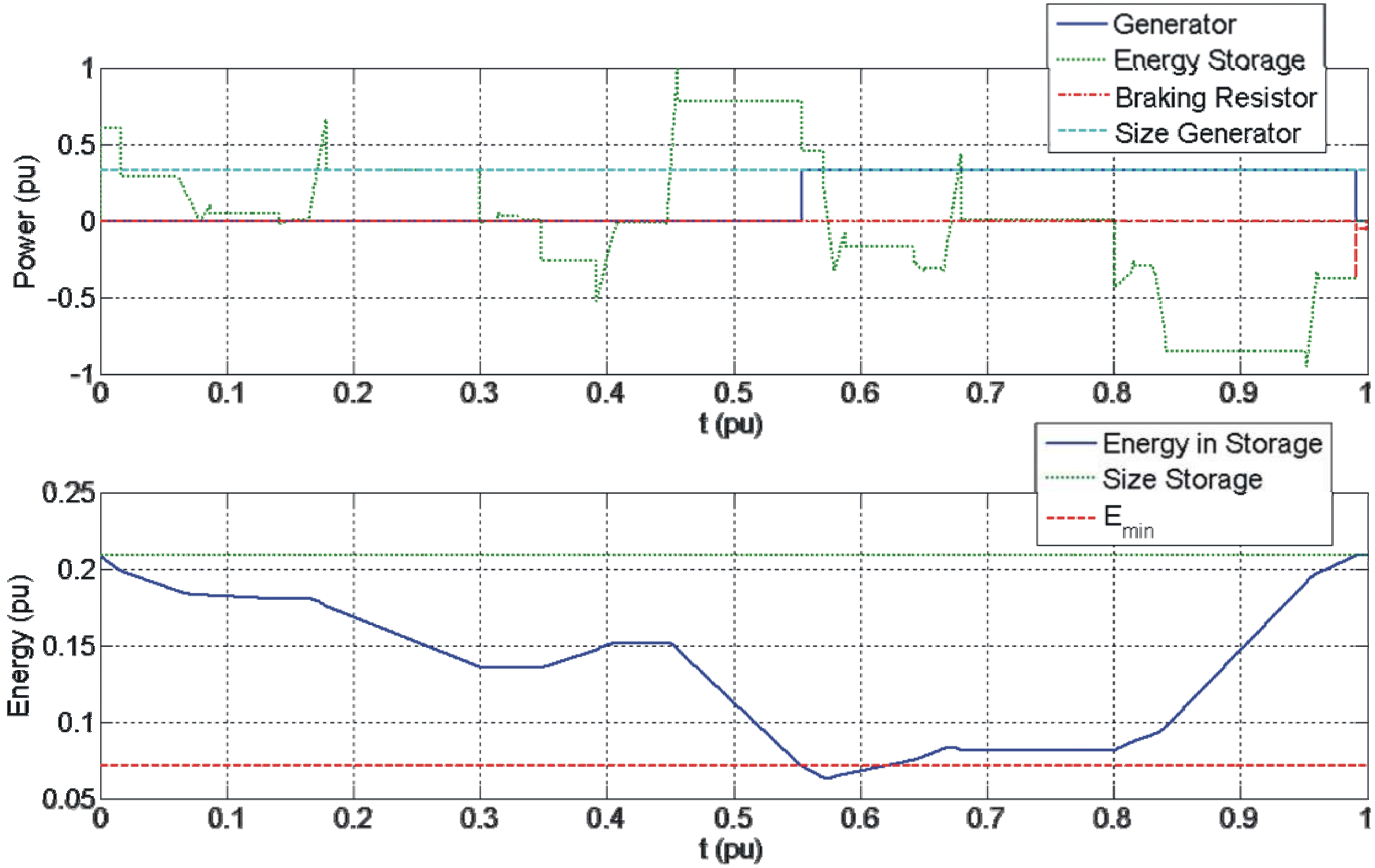
Dia 122

PB6 In the Max On or Off PMS (MOO), the generator supplies its maximum rated power or it is turned off. The generator is dimensioned in such a way that its power rating is higher than the average power needed
P Bauer; 27-5-2008

PB7 P Bauer; 28-5-2008

Max On or Off Power Management



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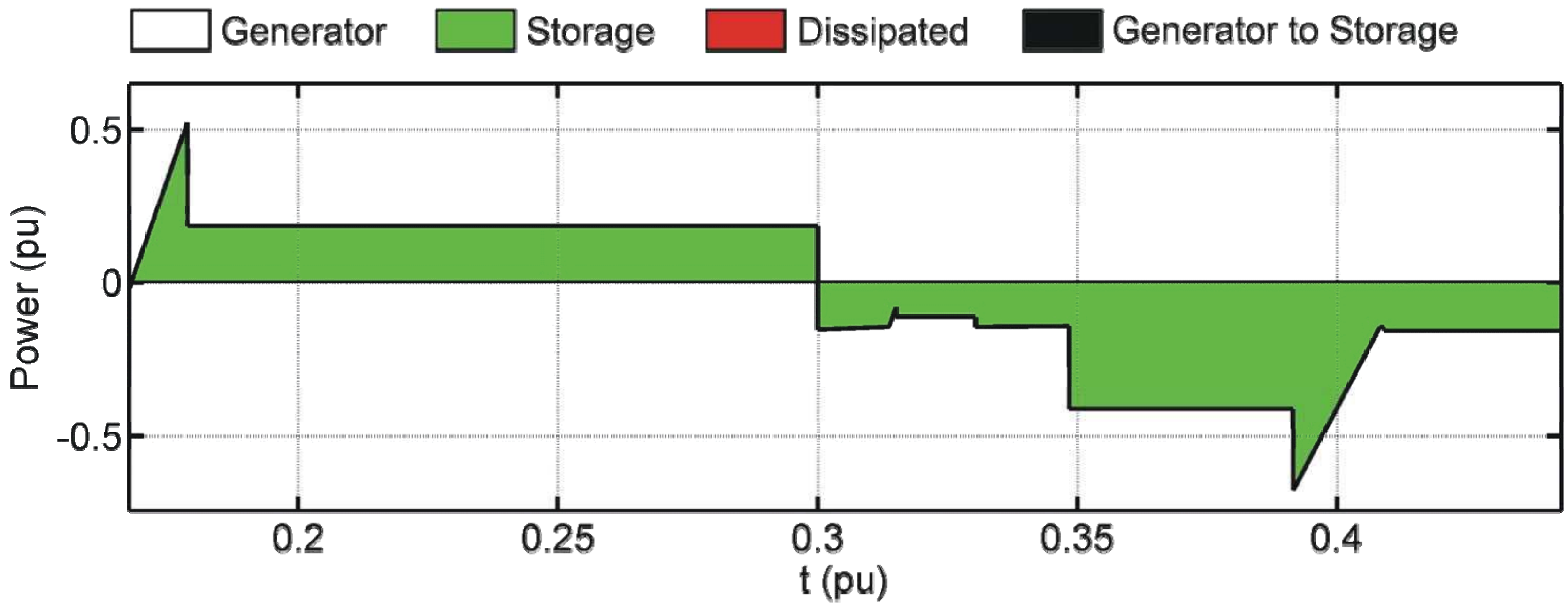
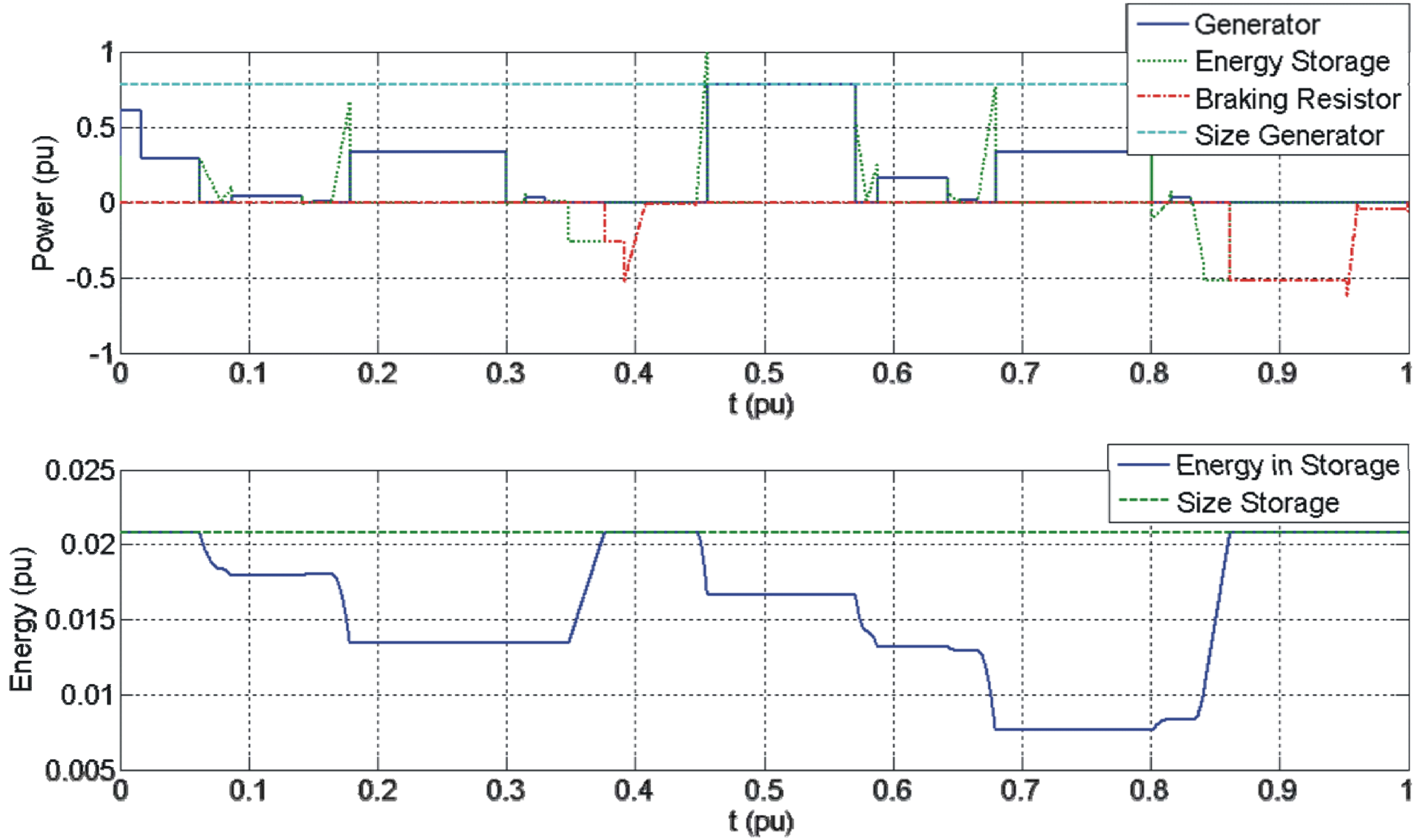
Only storage



PB8 The Only Storage PSM (OS) supplies only power from an energy storage device. The storage can be charged from the grid. Electricity from the grid is less expensive than electricity generated by a diesel generator (comparing [10] and [11]). Further unbalanced cycles becomes an option.
P Bauer; 27-5-2008

PB9 The energy storage becomes never empty. But after one cycle the storage element contains less energy. The decrease in energy is: . The fact that the energy in the energy storage decreases makes this system, for this case study, not feasible as stand alone system.
P Bauer; 27-5-2008

Only storage



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Figures of merit

- energy recovery factor

$$REC = \frac{E_{recovered}}{E_{regenerated}}$$

- dissipation factor

$$DIS = \frac{E_{dissipated}}{E_{regenerated}}$$

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Dia 126

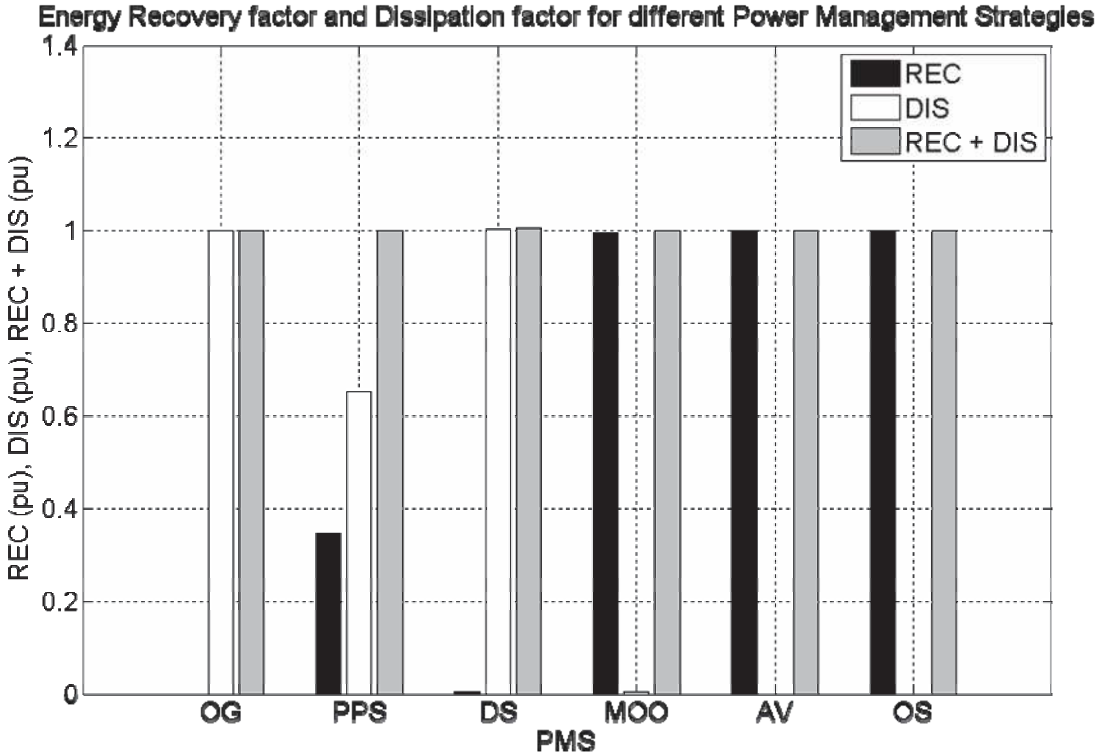
PB10 The energy recovery factor is the ratio between the total amount of energy that is recovered from the load and stored in the storage element ( ), and the total energy that could be recovered from the load (

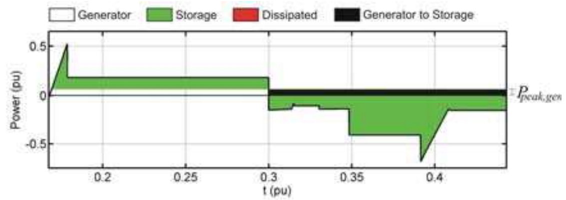
P Bauer; 27-5-2008

PB11 If , the dissipated and recovered energy is only the energy that could be recovered from the load. If, , energy is dissipated that comes straight from the generator. This is a disadvantageous situation.

P Bauer; 28-5-2008

Energy recovery





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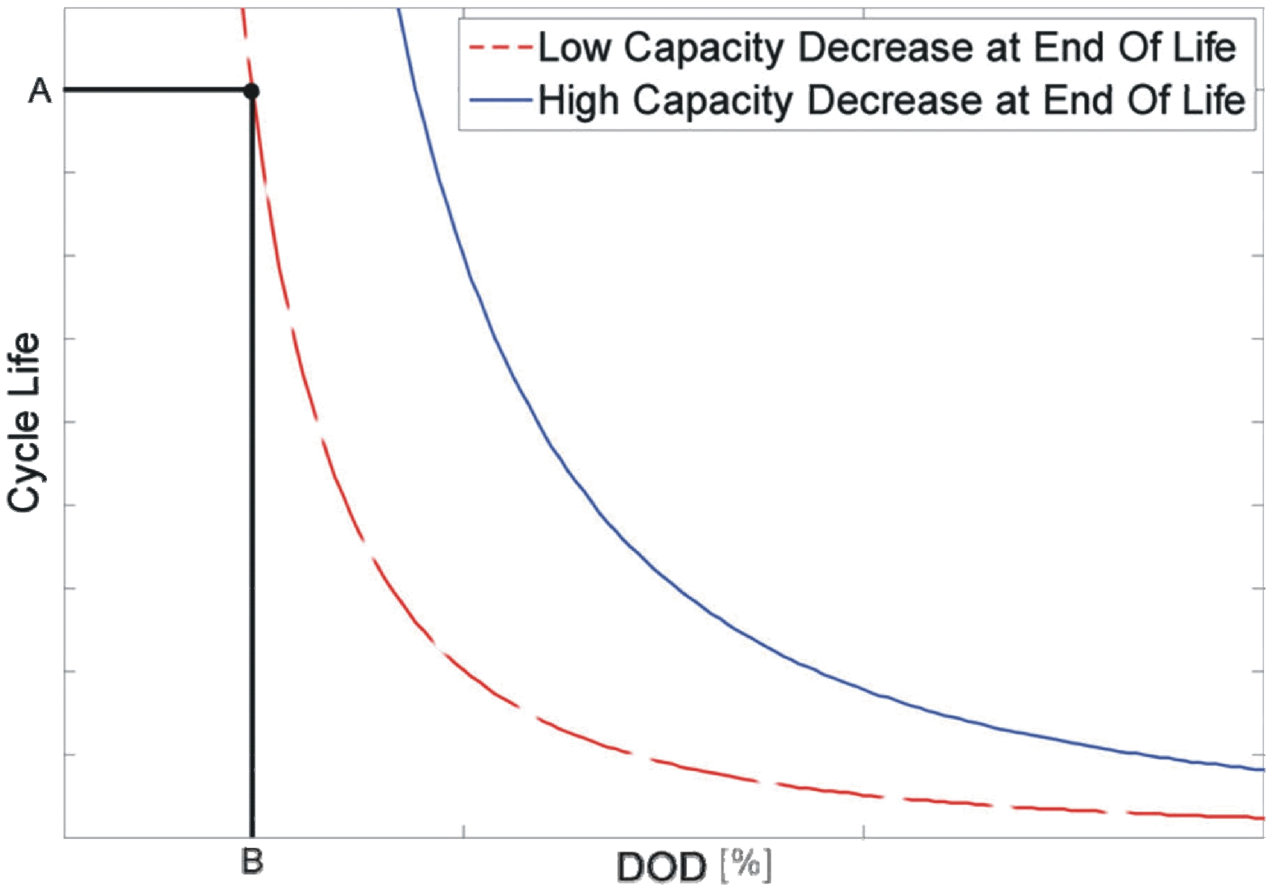
$$\text{cycle} = f(\text{DOD}, \text{EOL}) = x$$

$$\text{overSize}_{\text{Li-ion HP}} = \frac{1}{\text{EOL}} \cdot \frac{1}{\text{DOD}}$$



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Dia 128

PB12 The lifetime of a Li-ion HP battery is depended on the depth of discharge (DOD), number of cycles and the age [4]. The dependency on the DOD is not linear, a lower DOD means a much larger cycle life [4]. This relation is given schematically in Fig. 14. The lifetime of a Li-ion battery is 10 year [4, 13].

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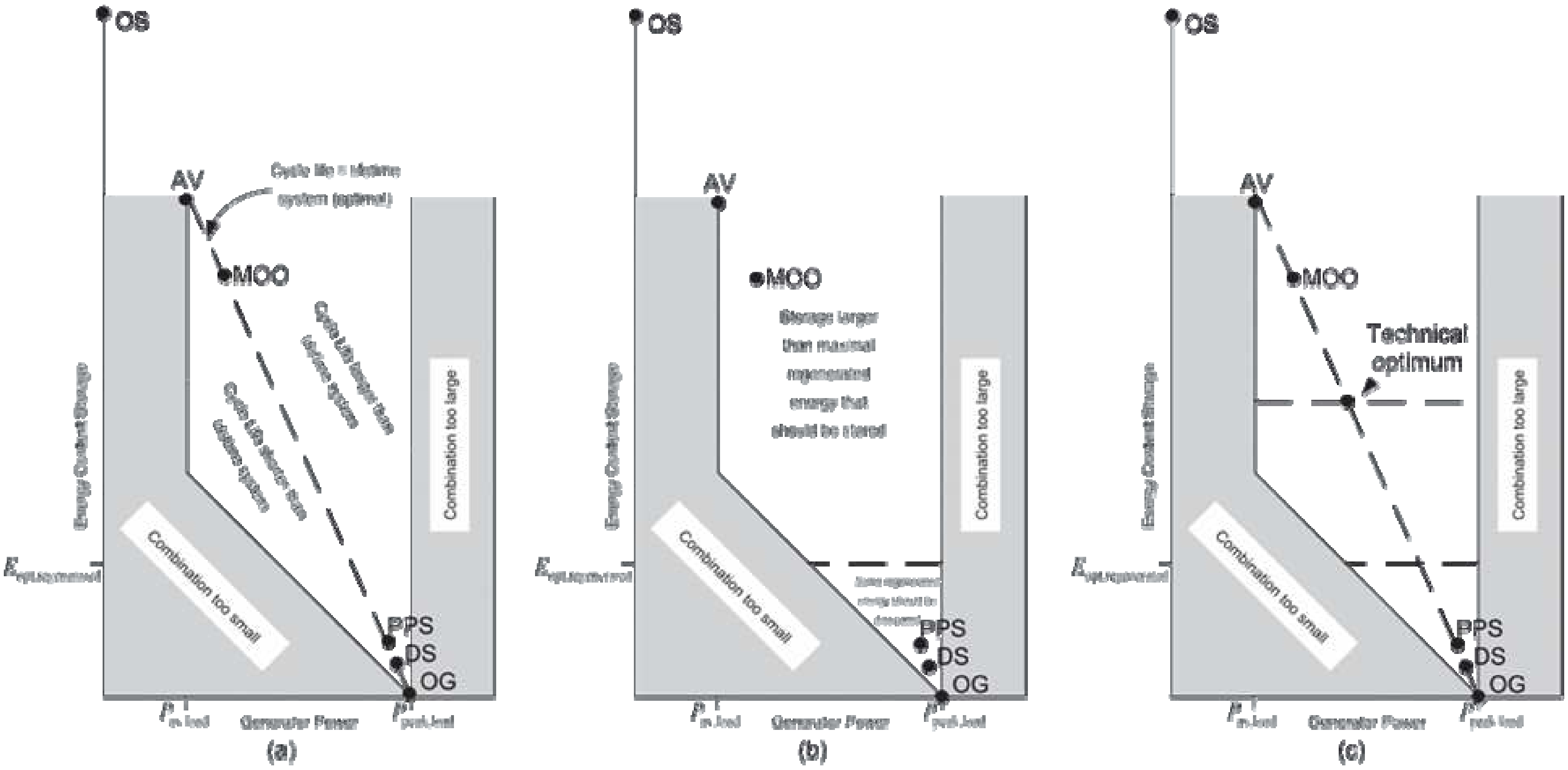
Sizes of the generator and storage



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Dia 129

PB13 From energy saving point of view an optimum can be found. This is the line where all regenerated energy can be stored in the energy storage. This is given with the horizontal line in

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PB14 For the lifetime for the Li-ion HP battery it was calculated in section V that the energy storage should be oversized with a factor 42,8 to get the optimal cycle life. This optimal cycle life is given by the dashed line in (Fig. 15a).

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PB15 Combining the optimal lines of (Fig. 15a) and (Fig. 15b) result in (Fig. 15c). The line for the optimal energy saving should be multiplied with the factor 42,8. The intersection of the obtained line and the optimal cycle life line gives an optimum. In the figure an illustration is given for the PMSs. The intersection found in (Fig. 15c) of the optimal cycle life line and the optimal energy line gives a theoretical technical optimum.

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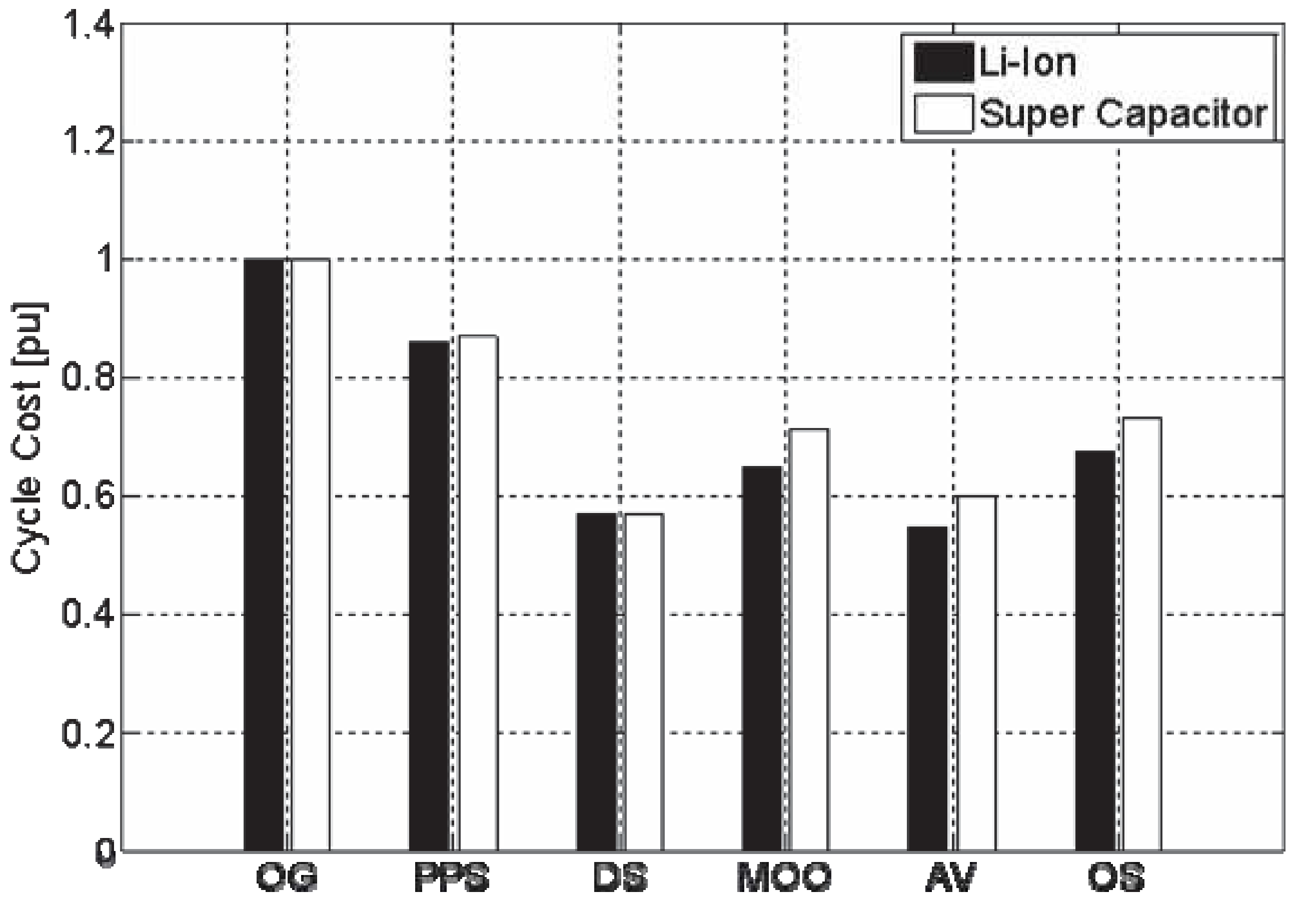
Comparison for costs for the different PMSs



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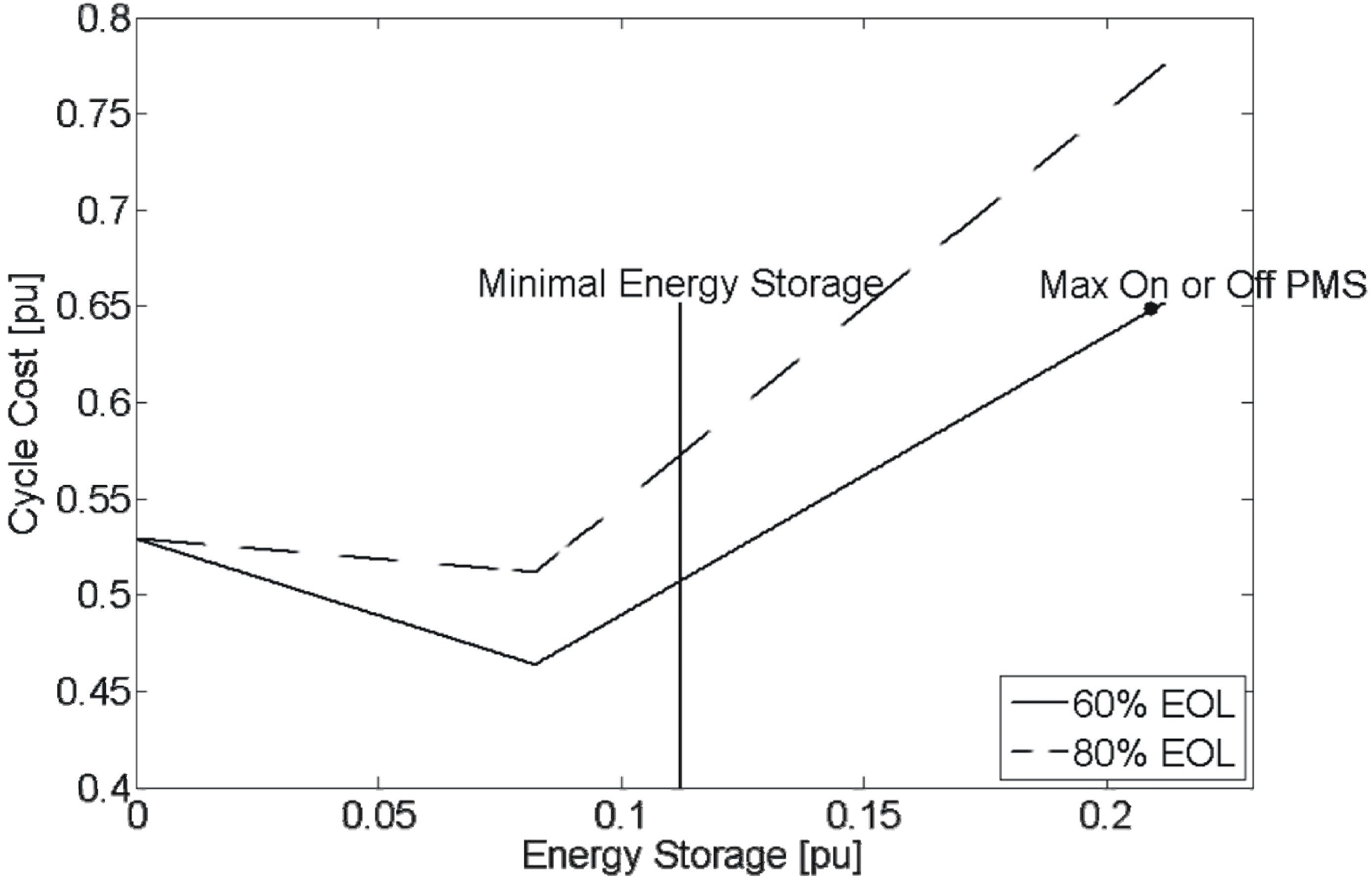
Minimal Energy Storage
Max On or Off PMS
Cycle Cost [pu]
Energy Storage [pu]
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0
0.05
0.1
0.15
0.2
60% EOL
80% EOL

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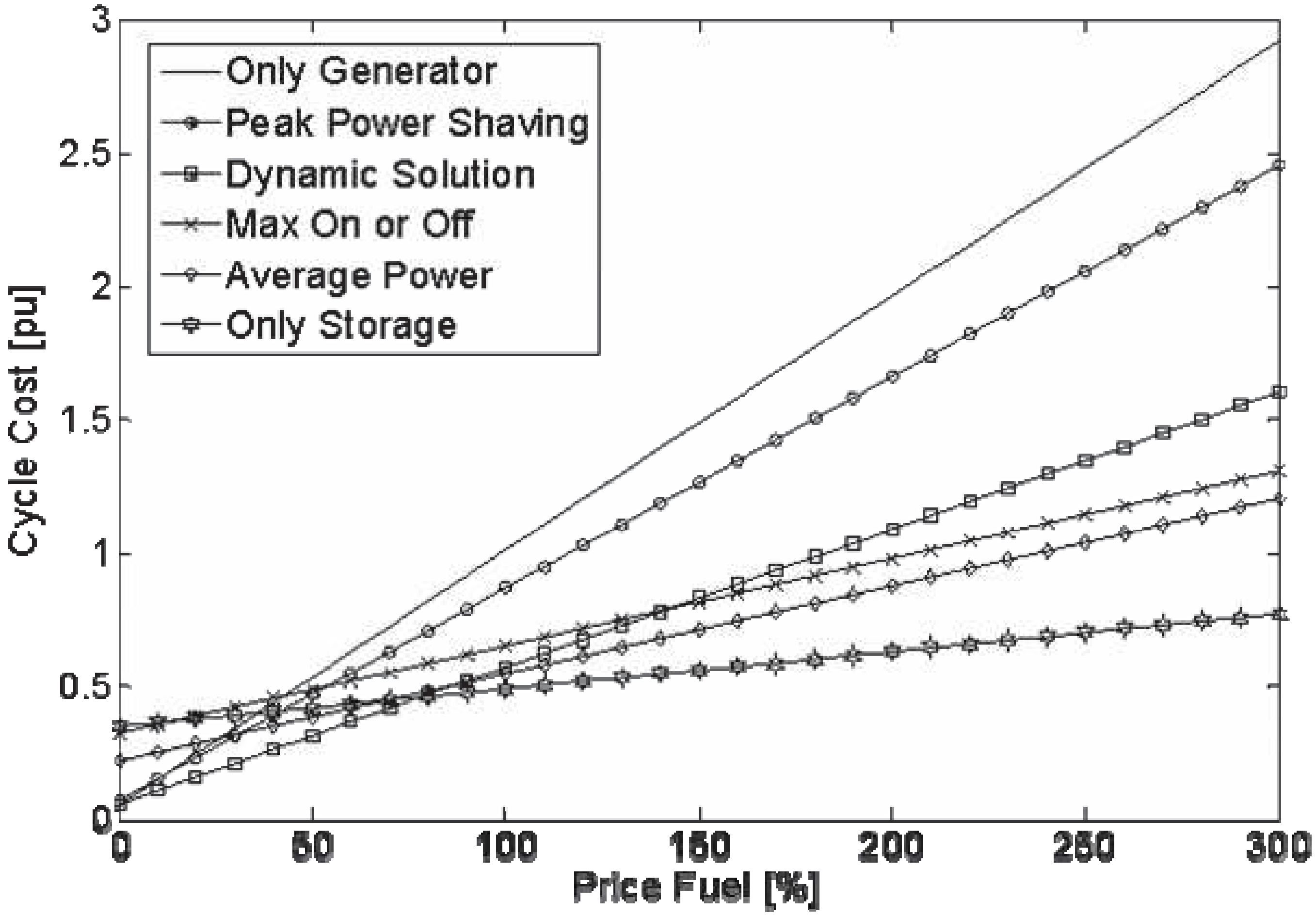
Data for cost calculation

$59 \cdot 10^3 \cdot P^{pu}_{nom,gen,peak} + 4676$ [€]

Parameter	Data	Source
Price fuel	1,00 [€/l]	[11]
Price electricity	0,10 [€/kWh]	[10]
Price Li-ion HP	2.000 [€/kWh]	[4]
Price super capacitor	45.000 [€/kWh]	[13]
Price generator	$59 \cdot 10^3 \cdot P^{pu}_{nom,gen,peak} + 4676$ [€]	[20]
Price power electronics	75 [€/kW]	[7]
Caloric value diesel	35.700 [kJ/l]	[21]
Fuel efficiency generator	43 %	[22]

Sensitivity study: Variable Fuel Prices



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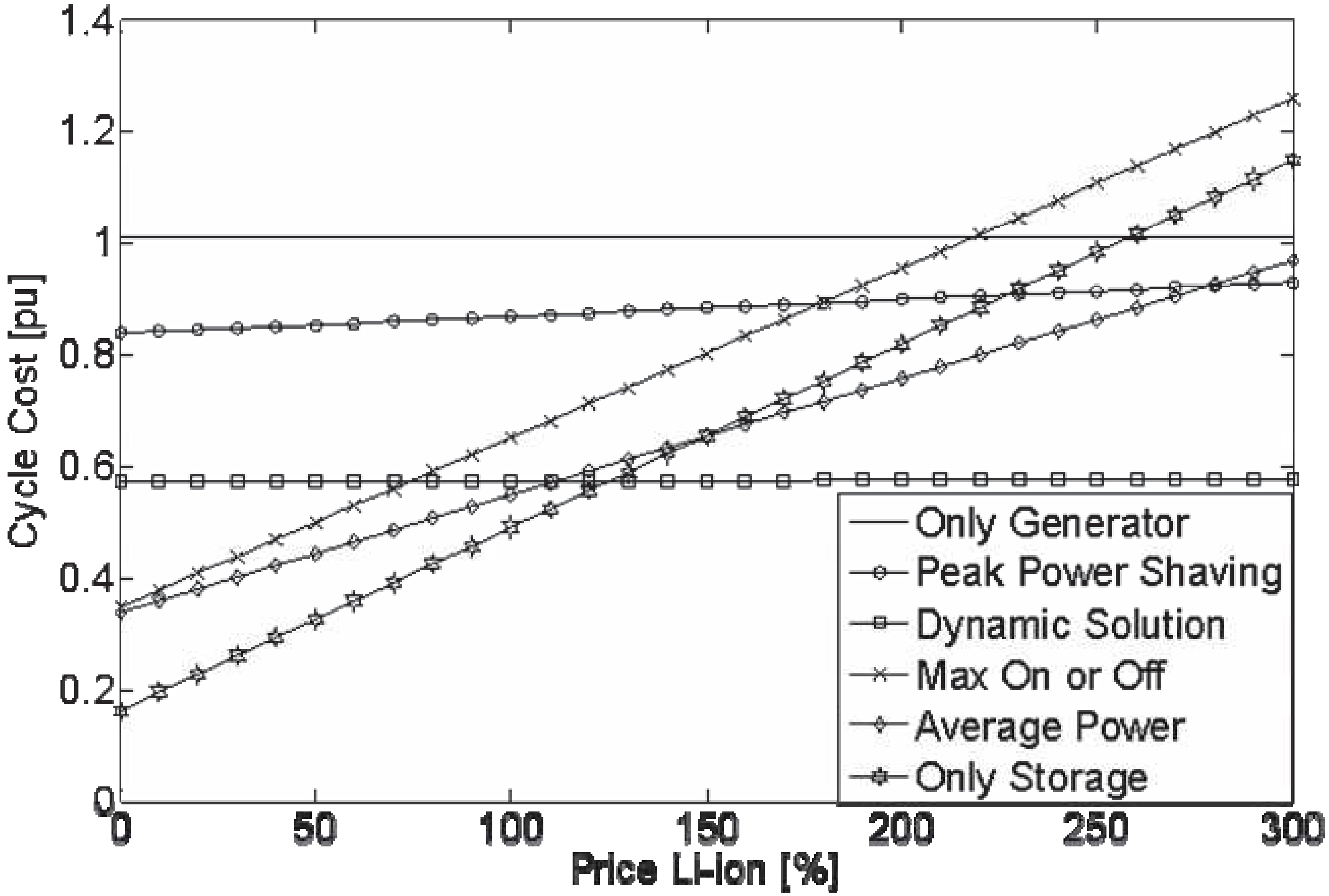
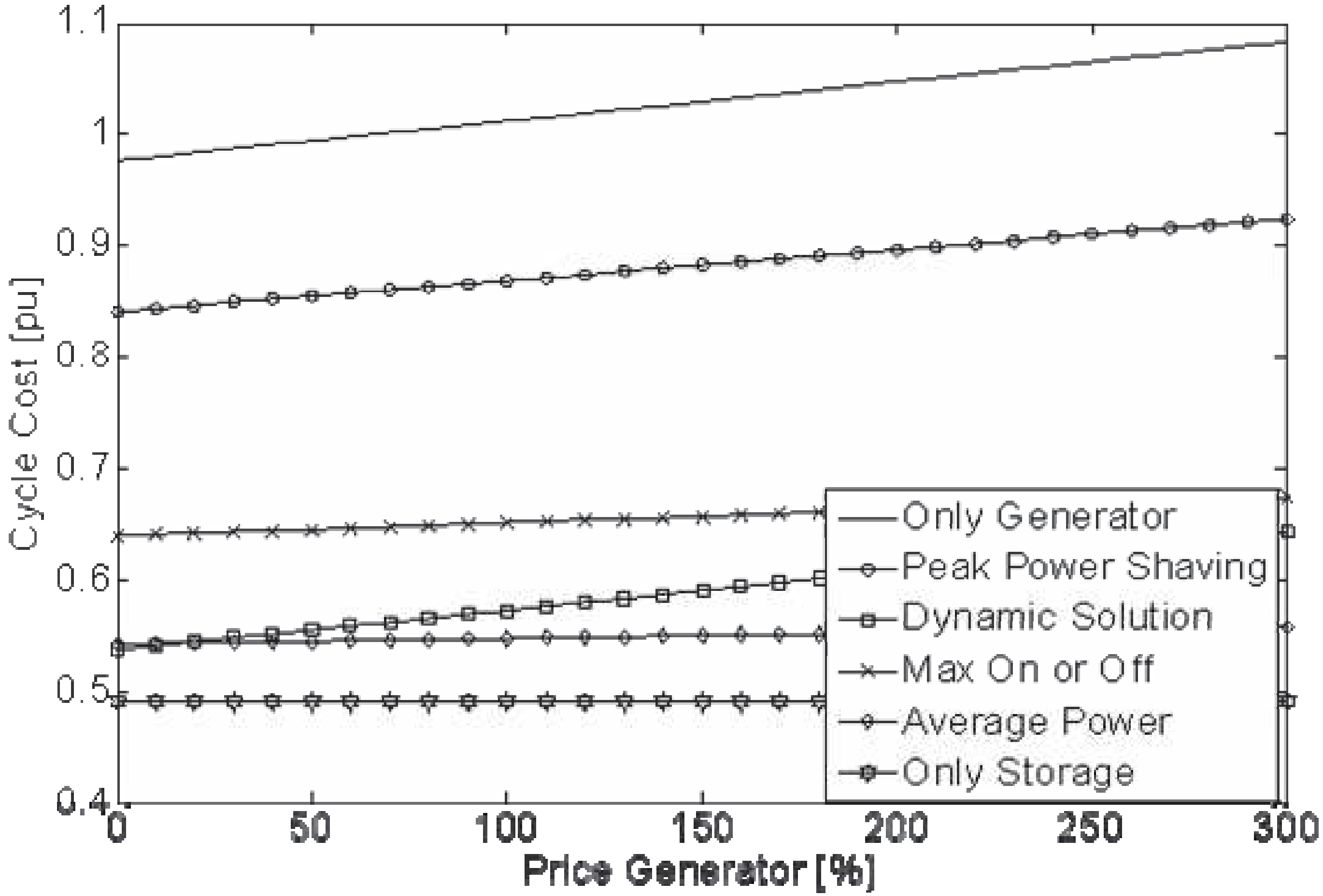
Sensitivity study: Variable Li-ion Prices



Sensitivity study: Variable Generator Prices



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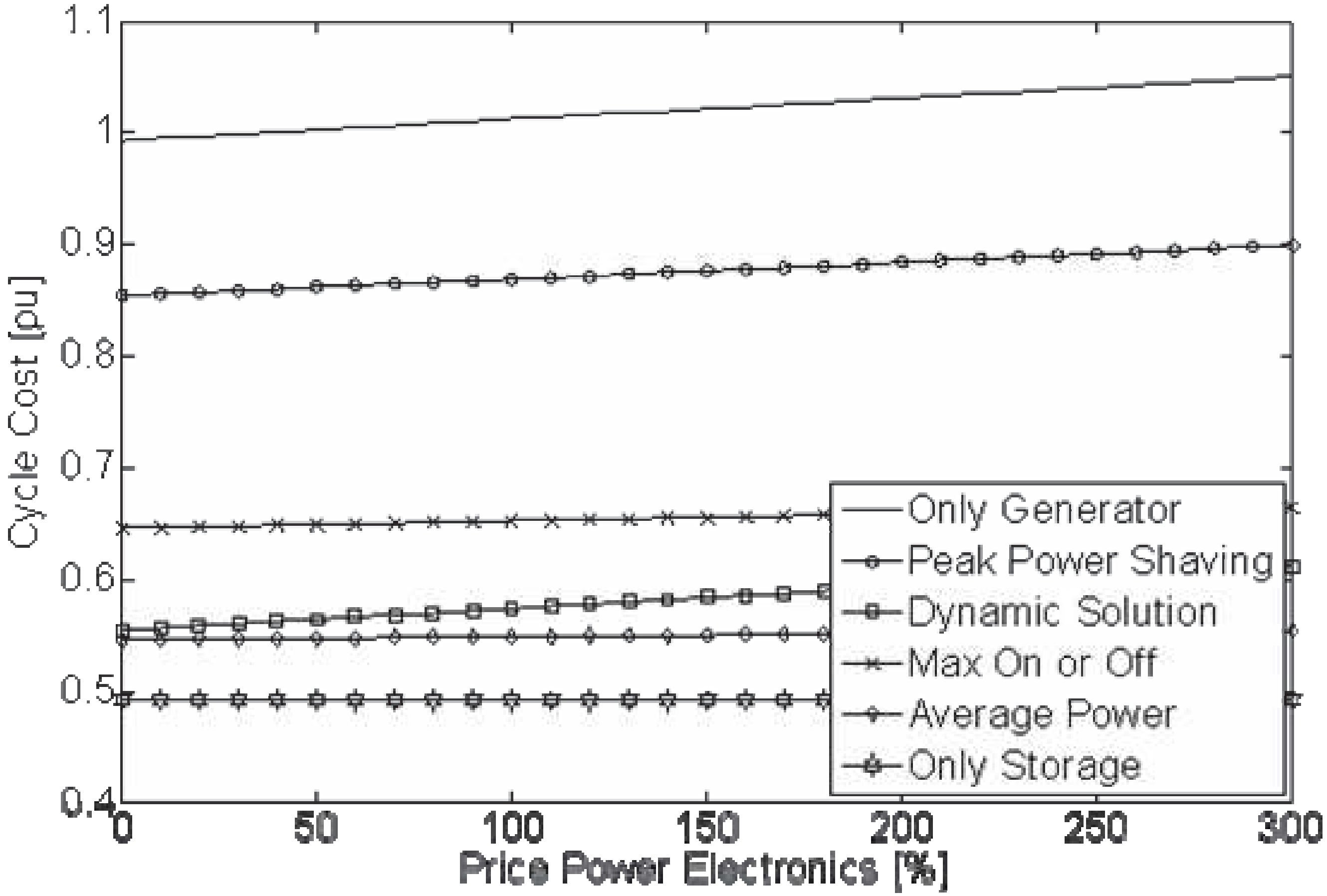
Sensitivity study: Variable Power Electronics Price



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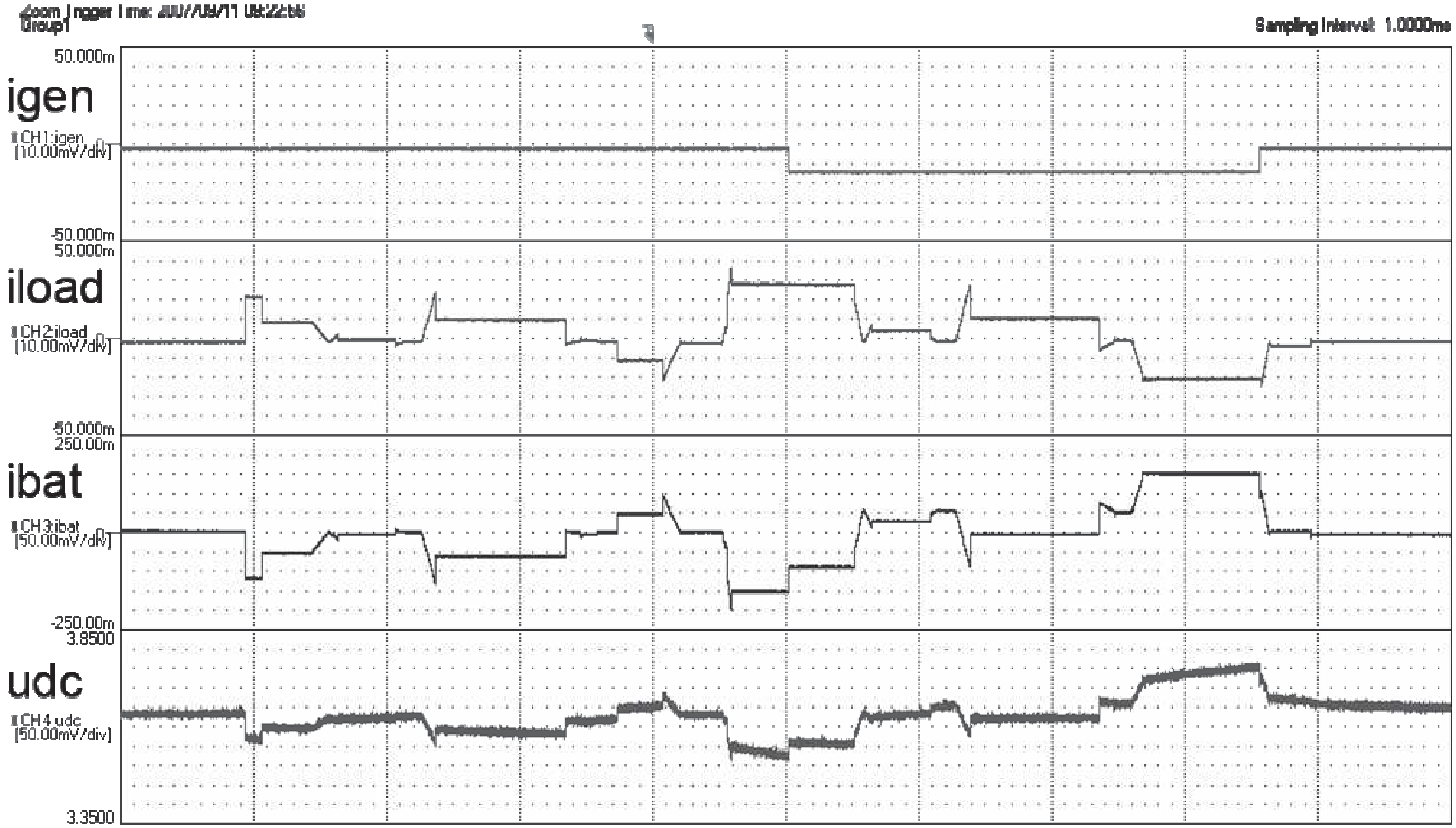
Experimental verification Max On Off



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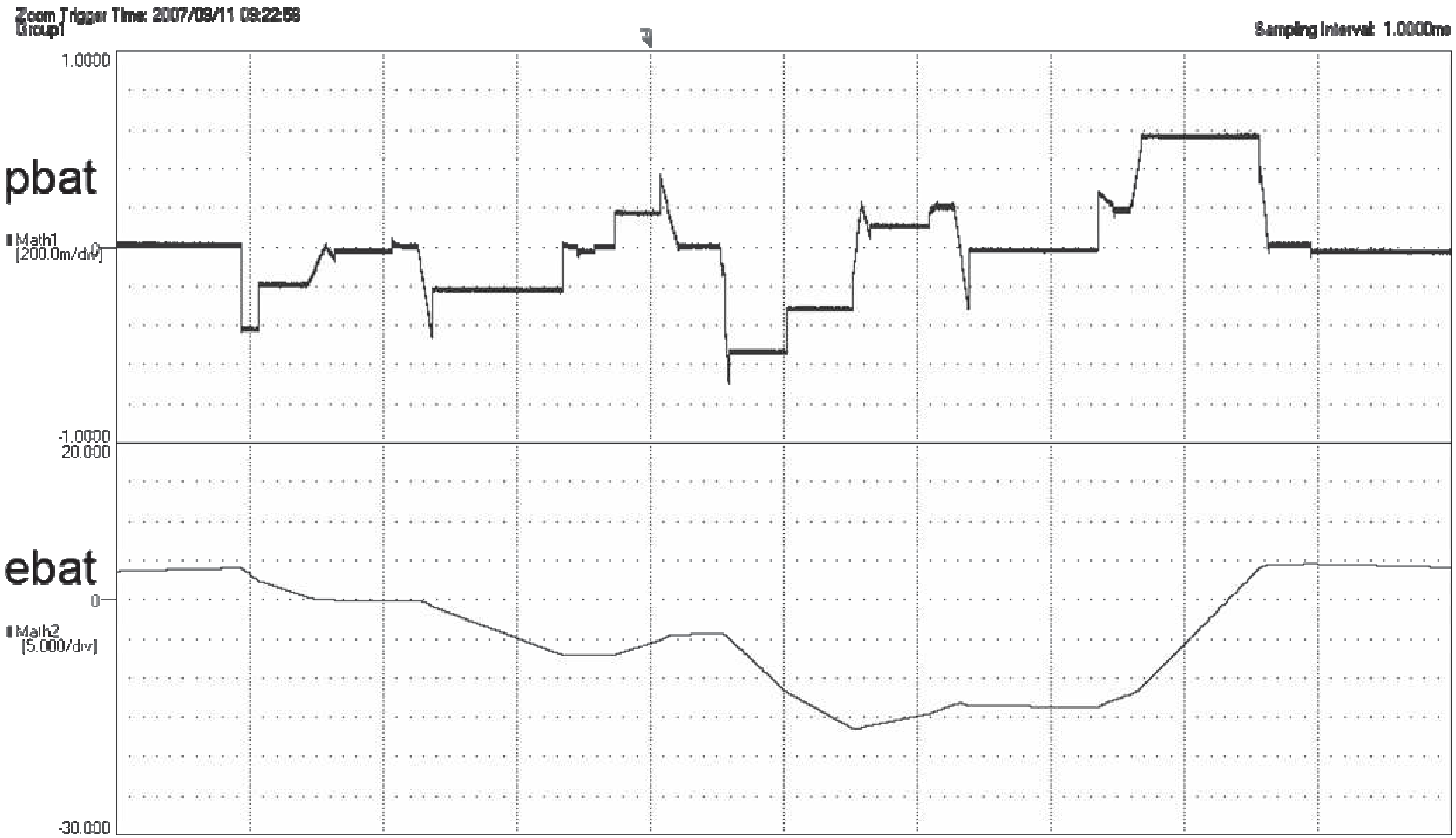
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Conclusions

- Six different pms are defined
- Fuel prices and storage prices are the most sensitive element
- After an increase of 40%of fuel prices and 25% decrease of Li-ion

  prices the Max On or Off method has an advantage over the dynamic solution