HYDROGEMS

Hydrogen Energy ModelS

Version 1.1

PV	DEGS	WECS
Electrolysis	PEMFC	AFC
DC / AC	Battery	Storage

Institute for Energy Technology

Vision of HYDROGEMS:

To provide modeling 'gems' for anyone seeking
to simulate integrated hydrogen systems
based on renewable energy.

Hydrog$_{en}$ E$_{nergy}$ M$_{odel}$^{S}

DEVELOPERS

Øystein Ulleberg
oysteinu@ife.no

Ronny Glöckner
ronnyg@ife.no

Institute for Energy Technology
P.O. Box 40
N-2007 Kjeller
Norway

ACHOWLEDGEMENTS

(in chronological order)

Svein Mørner, Norwegian University of Science and Technology (NTNU), Trondheim
Per Finden, Institute for Energy Technology (IFE), Kjeller
Bjørn Gaudernack, IFE
Fritjof Salvesen, Norwegian Research Council (NFR), Oslo
Trygve Riis, NFR
Wennemar A. Brocke, Forschungszentrum Jülich (FZJ), Germany
Jürgen Mergel, FZJ
Prof. William A. Beckman, University of Wisconsin (UW), Madison
Prof. Sandy Klein, UW-Madison
Werner Keilholz, Centre Scientifique et Technique du Batiment (CSTB) , Sophia Antipolis, France
Cathy Gregoire Padró, National Renewable Energy Laboratory (NREL), Golden, Colorado
Pietro d'Erasmo, Norsk Hydro Electrolysers AS, Notodden, Norway
Trevor Pryor, Murdoch University Energy Research Instiute (MUERI), Western Australia
Bob Lloyd, Australian Center for Renewable Energy (ACRE), Murdoch, Western Australia
Anna Carr, MUERI

FINANCING

Norwegian Research Council, Oslo

TRIBUTE

Prof. Odd A. Asbjørnsen

ABSTRACT

HYDROGEMS is a collection of HYDROGen Energy ModelS intended for integrated renewable–hydrogen (RE–H_2) energy system simulations. The HYDROGEMS library includes component subroutines for photovoltaic (PV) arrays, wind energy conversion systems (WECS), diesel engine generator systems (DEGS), advanced alkaline water electrolysis, high-pressure hydrogen gas storage, metal hydride (MH) storage, proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC), compressors, power conditioning equipment, and logical control functions. HYDROGEMS is a result of 7 years of modeling and simulation work on stand-alone power systems (SAPS) undertaken at the Institute for Energy Technology (IFE). The models have been tested and verified against various RE–H_2 energy demonstration plants around the world. HYDROGEMS have been made compatible to a transient system simulation program (TRNSYS), which makes it possible to integrate the component models with a standard library of thermal and electrical renewable energy components. Some of the key HYDROGEMS components (PV, WECS, electrolyzer, and fuel cells) are also available as external functions for EES, an engineering equation solver, which has built-in functions for thermodynamic and transport properties of many substances, including steam, air, air-water vapor mixtures (psychrometrics), refrigerants, cryogenic fluids, JANAF table gases, and hydrocarbons. This makes HYDROGEMS particularly useful for (1) System design (or redesign) and (2) Optimization of control strategies for integrated RE–H_2 energy systems.

TABLE OF CONTENTS

TYPE180
Photovoltaic Generator
Version 4.0

Abstract

TYPE180 is a mathematical model for a photovoltaic (PV) generator, based on an equivalent circuit of a one-diode model. The model is primarily intended for PV-arrays consisting of silicon cells, but can also be used for other types of materials. The electrical model used in TYPE180 is described in (Duffie and Beckman, 1991). A dynamic thermal model has also been included (Ulleberg, 1997; 1998).

Overview

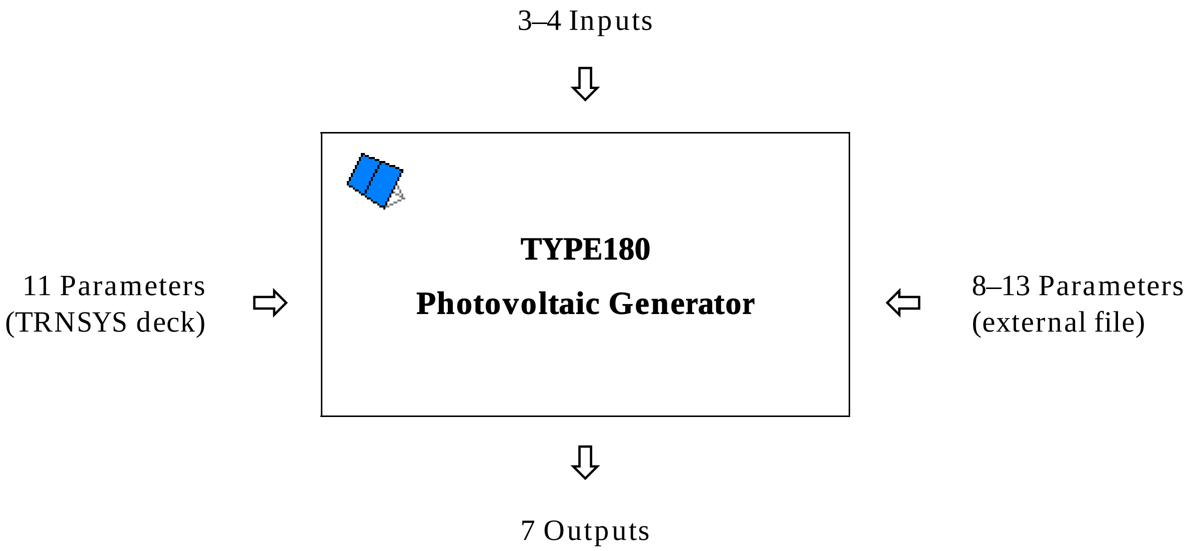

Figure 1 TYPE180 information flow

Inputs & Outputs

Table 1 TYPE180 - Inputs

#	Input	Units	Description
1	γ	-	0 = OFF, 1 = ON
2	G_T	W / m^2	Incident solar radiation flux
$T_{c,mode}$ = 1:			
3	T_{cell}	°C	PV cell temperature
$T_{c,mode}$ = 2 or 3:			
3	T_{amb}	°C	Ambeint temperature
MPPT = OFF:			
4	U	V	Voltage across PV-array

Table 2 TYPE180 - Outputs

#	Output	Units	Description
1	I	A	Electrical current
2	U	V	Voltage across PV-array
3	P	W	Power
4	η	0…1	Efficiency
5	T_{cell}	°C	Cell temperature
6	I_{sc}	A	Short circuit current for PV-array
7	U_{oc}	V	Open circuit voltage for PV-array

Parameters

Table 3 TYPE180 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	MPPT	1	-	Maximum Power Point Tracker mode MPPT = 0: OFF MPPT = 1: ON
2	$T_{c,mode}$	1	-	Cell temperature mode $T_{c,mode}$ = 1: T_{cell} is given $T_{c,mode}$ = 2: Static thermal model $T_{c,mode}$ = 3: Dynamic thermal model
3	$n_{c,ser}$	150	-	Number of cells in series in a single PV-module
4	$n_{m,ser}$	4	-	Number of PV-modules in series in PV-array
5	$n_{m,par}$	14	-	Number of PV-modules in parallel in PV-array
6	*Area*	1.5	m^2	Area (single PV-module) covered with PV cells
7	$\tau\alpha$	0.9	-	Reflectance-absorptance product; τ = transmittance of PV-cover α = fraction absorbed on the cell surface
8	E_{gap}	1.12	eV	Energy band gap for silicon
9	R_{sh}	1e6	Ω	Shunt resistance
10	PV_{type}	5	-	Type of PV panel
11	LU		-	Logical Unit for file with PV parameters

Table 4 TYPE180 – Parameters (external file)

#	Parameter	Example	Units	Description
1	$I_{sc,ref}$	2.664	A	Short circuit current at reference
2	$U_{oc,ref}$	87.720	V	Open circuit voltage at reference
3	$T_{c,ref}$	25	°C	Reference cell temperature
4	$G_{T,ref}$	1000	W/m^2	Reference solar radiation
5	I_{mp}	2.448	A	Maximum current at reference
6	U_{mp}	70.731	V	Maximum voltage at reference
7	$\mu_{I,sc}$	0.00148	A/K	Short circuit current temperature coefficient
8	$\mu_{U,oc}$	-0.3318	V/K	Open circuit voltage temperature coefficient
<u>$T_{c,mode}$ = 2</u>:				
9	$T_{a,NOCT}$	20	°C	Ambient temperature at NOCT (Nominal Operating Cell Temperature)
10	$T_{c,NOCT}$	44	°C	Cell temperature at NOCT
11	$G_{T,NOCT}$	800	W/m^2	Solar radiation at NOCT
<u>$T_{c,mode}$ = 3</u>:				
12	U_L	30	J/m^2	Overall heat loss coefficient for PV module
13	C_t	50000	$J/m^2{\cdot}K$	Thermal capacitance of PV module

Note! Values for all 13 parameters must be listed in the external file. Only parameters 1–8 are needed in $T_{c,mode}$ = 1. Parameters 1–11 are needed in $T_{c,mode}$ = 2, while parameters 1–13 are needed in $T_{c,mode}$ = 3.

Source Code & Related Programs

Table 5 TYPE180 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE180.FOR	4.0	2001.03.12
EES source code	PVMODULE.FOR	1.0	1999.09.21
EES program	PVMODULE.EES	1.0	2001.02.09

References

Duffie J. A. and Beckman W. A. (1991) *Solar Engineering of Thermal Processes*. 2nd edn, Wiley Interscience, New York.

Ulleberg Ø. (1997) Simulation of autonomous PV-H2 systems: analysis of the PHOEBUS plant design, operation and energy management. In *Proceedings of ISES 1997 Solar World Congress*, August 24-30, Taejon, Korea.

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems*. PhD thesis, Norwegian University of Science and Technology, Trondheim.

TYPE190

Wind Energy Conversion System

Version 4.0

Abstract

TYPE190 is a mathematical model for a wind energy conversion system (WECS). The model calculates the power output of a WECS based on a power versus wind speed characteristic (provided on table form in an external file). The impact of air density changes and wind speed increases with height is also modeled. The main equations used in this model is based on the work of (Quinlan, 2000; Quinlan *et al.*, 1996). TYPE190 is an improved and modified version of TYPE90 found in (Klein *et al.*, 2000).

Overview

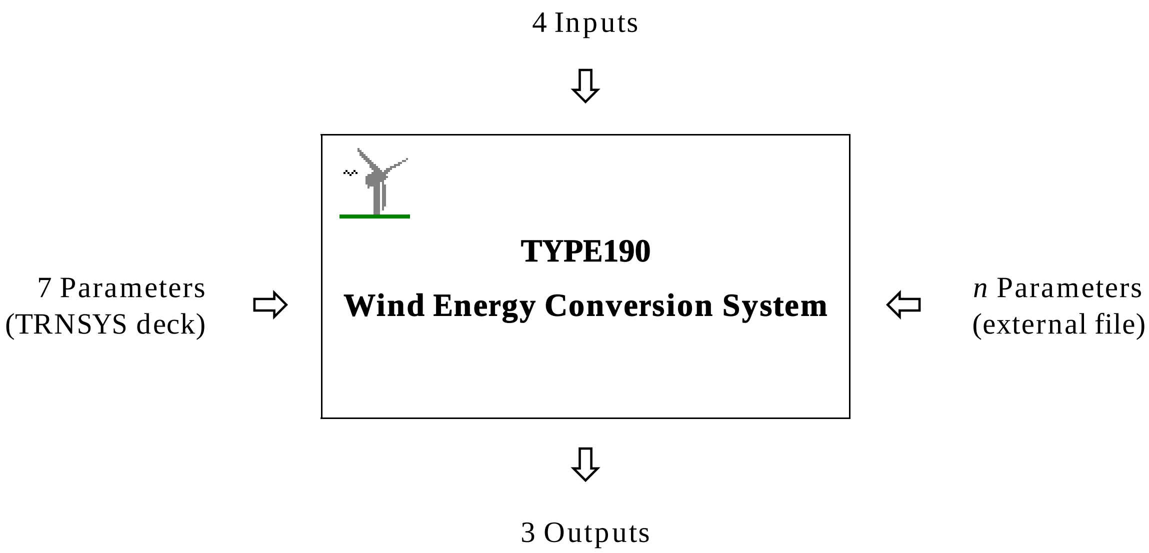

Figure 2 TYPE190 information flow

Inputs & Outputs

Table 6 TYPE190 - Inputs

#	Input	Units	Description
1	v_{speed}	m/s	Wind speed
2	T_{amb}	°C	Ambient temperature
3	α_{site}	-	Site wind shear component -0.06 = inverted profile 0.00 = neutral profile 0.06 = open water 0.10 = short grass 0.14 = common profile = 1/7 0.18 = low vegetation 0.22 = forest 0.26 = obstructed flows 0.30 = rare
4	p_{bar}	Pa	Barometric pressure*

Note! p_{bar} is currently not used; a model for calculating p_{bar} based on T_{amb} and $Site_{elev}$ is used instead.

Table 7 TYPE190 - Outputs

#	Output	Units	Description
1	$P_{WECS,net}$	W	Net power output
2	Hours	hr	Hours of continous WECS operation
3	CP	-	Power coefficient

Parameters

Table 8 TYPE190 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	Mode	1	-	Turbine operation status (1=ON, 0=OFF)
2	$Site_{elev}$	0	m	Site elevation
3	$Site_{Ht}$	30	m	Site data collection height
4	$Site_{RoHt}$	46	m	Hub height of WECS, as installed on site
5	Lost	0.0	-	Miscellaneous losses
6	Num		-	Number of exactly similar turbines
7	LU		-	Logical unit for external file WECS parameters

Table 9 TYPE190 – Parameters (external file)

#	Parameter	Example	Description
1	WECS_Typ	Vestas V66 1650/66	Type of WECS (manufacturer’s model name)
2	WECS_Ref	windpower.dk	Source of data
3	Len_Unit	m	Length unit
4	Spd_Unit	m/s	Wind speed units
5	Pwr_Unit	kW	Power output units
6	Ctl_mode	P	Control mode; S=Stall, P=Pitch, V=Variable Speed (P & V is essentially power regulation at high wind speeds)
7	Rotor_Ht	67.00	Rotor center height, m
8	Rotor_Di	66.00	Rotor diameter, m
9	Sensr_Ht	67.00	Sensor Height for data, m (In brochures for commercial WECS, 'Rotor_Ht' usually equals 'Sensor_Ht')
10	Sher_Exp	0.14	Power-law exponent for speed-up calculation (Only needed when 'Rotor_ht' and 'Sensor_Ht' differ)
11	Turb_Int	0.10	Turbulence intensity valid for this curve (Not used in TYPE190)
12	Air_Dens	1.225	Power curve air density, kg/m3 (Usually at T = 15°C and p = 101.325 kPa)
13	Pwr_Ratd	1650.00	Rated power of the turbine (Only applicable for pitch and variable speed regulated WECS)
14	Spd_Ratd	17.00	Wind speed at rated power (Only applicable for pitch and variable speed regulated WECS)
15	Num_Pair	26	The number of power versus windspeed pairs
16	0.00	0.00	Windspeed - Power pair no.1 -start at zero
17	1.00	0.00	Windspeed - Power pair no.2
18	2.00	0.00	Windspeed - Power pair no. 3
…	…	…	…
n	25.0	1650.00	Maximum 100 pairs

Source Code & Related Programs

Table 10 TYPE190 related source code & EXCEL program files

Description	File name	Version	Date
TRNSYS source code	TYPE190.FOR	4.0	2001.02.28
EXCEL data base 1	Danish WECS.XLS	1.0	2001.03.27
EXCEL data base 2	More WECS.XLS	1.0	2001.07.24

References

Klein S. A., Beckman W. A., Mitchell J. W., Duffie J. A., Duffie N. A., Freeman T. L., Mitchell J. C., Braun J. E., Evans B. L., Kummer J. P., Urban R. E., Fiksel A., Thornton J. W., Blair N. J., Williams P. M. and Bradley D. E. (2000) *TRNSYS – A Transient System Simulation Program*. Manual, v15, Solar Energy Laboratory, University of Wisconsin, Madison.

Quinlan P. J. (2000) A time-series wind turbine array simulator. In *Proceedings of ASES Conference SOLAR 2000*, June, Madison, Wisconsin.

Quinlan P. J., Beckman W. A., Mitchell J. W., Klein S. A. and Blair N. J. (1996) Time series modeling of hybrid wind/photovoltaic/diesel power systems. In *Proceedings of ASES Conference SOLAR 1996*, Asheville, North Carolina.

TYPE170

Proton Exchange Membrane Fuel Cell

Version 4.0

Abstract

TYPE170 is a generic mathematical model for a proton exchange membrane fuel cell (PEMFC). The model is largely mechanistic, with most terms being derived from theory or including coefficients that have a theoretical basis. The major nonmechanistic term is the ohmic overvoltage that is primarily empirically based. The main equations of the electrochemical model are described in published literature (Amphlett *et al.*, 1995a; 1995b; Mann *et al.*, 2000). A thermal dynamic model is also included. The theory behind the thermal model is found in previous PEMFC-modeling work (Ulleberg, 1998), while the recommended thermal coefficients were derived from two sources (Amphlett *et al.*, 1996; Ulleberg, 2001).

Overview

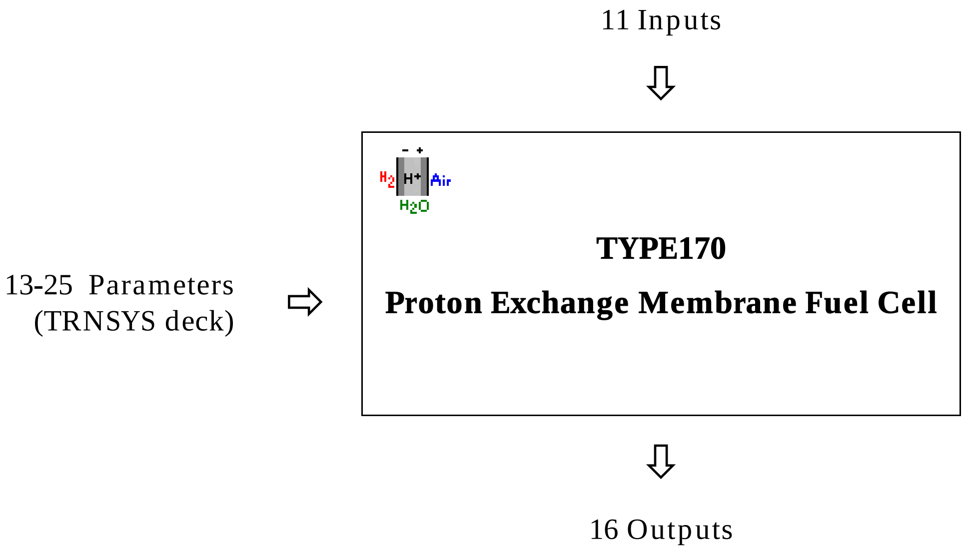

Figure 3 TYPE170 information flow

Inputs & Outputs

Table 11 TYPE170 - Inputs

#	Input	Example	Units	Description
1	γ	1	-	0 = OFF, 1 = ON
2	I_{FC}	100	A	Total fuel cell current
TMODE = 1:				
3	T_{FC}	70	°C	Average FC stack temperature
TMODE = 2:				
3	$T_{FC,set\ point}$	70	°C	FC set point temperature
4	$p_{H2,in}$	3	bar	Hydrogen inlet pressure
OXMODE = 1:				
5	$p_{Air,in}$	3	bar	Air inlet pressure
OXMODE = 2:				
5	$p_{O2,in}$	3	bar	Oxygen inlet pressure
6	S_{H2}	1.15	-	Stoichiometric ratio for hydrogen
7	S_{ox}	2.5	-	Stoichiometric ratio for oxidant
8	T_{amb}	20	°C	Ambient temperature
9	$T_{cw,in}$	15	°C	Cooling water inlet temperature
10	ΔT_{cw}	20	°C	Temperature rise of cooling water
11	X_{evap}	0.25	-	Evaporation rate of process water

Table 12 TYPE170 - Outputs

#	Output	Units	Description
1	P_{FC}	W	Fuel cell power output
2	U_{STACK}	V	Voltage across each stack in parallel
3	η_e	0…1	Energy effiency
4	$I_{FC,D}$	mA/cm^2	Current density
5	U_{cell}	V	Cell voltage
6	V_{H2}	Nm^3/hr	Hydrogen consumption
OXMODE = 1:			
7	V_{air}	Nm^3/hr	Air consumption
OXMODE = 2:			
7	V_{O2}	Nm^3/hr	Oxygen consumption
8	Q_{gen}	W	Heat generated by fuel cell
9	Q_{cool}	W	Auxiliary cooling requirement
10	Q_{loss}	W	Heat loss to the ambient
11	Q_{evap}	W	Heat tranfer due to evaporation
12	Q_{heat}	W	Auxiliary heating requirement
13	V_{cool}	m^3/hr	Total cooling/heating water consumption
14	T_{stack}	°C	Average fuel cell stack temperature
15	R_t	K/W	Thermal resistance per stack
16	C_t	J/K	Thermal capacity per stack

Parameters

Table 13 TYPE170 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	OXMODE	1	-	Type of oxidant fed to the cathode OXMODE = 1: Air OXMODE = 2: pure oxygen
2	TMODE	1	-	Temperature mode TMODE = 1: Static model (T_{FC} is given) TMODE = 2: Dynamic model
3	n_{cells}	35	-	Number of cells in series per stack
4	n_{stacks}	1	-	Number of stacks in parallel per unit
5	A_{PEM}	232	cm^2	Electrode area (cross-sectional) of PEM
6	t_{PEM}	0.0118	cm	Thickness of PEM
7	γ	0.0	-	Transport number for water 0.0 = Well hydrated PEM 1.2 = Water deficient or lean-water PEM
8	$U_{c,min}$	0.7	V	Minimum allowable cell voltage
9	i_{max}	700	mA/cm^2	Maximum allowable current density
10	$RTCT_{Mode}$	1		Modes for calculating thermal coefficients
RTCTMODE = 1:				
11	h_{air}	40	$W/m^2{\cdot}K$	Heat transfer coefficient to ambient air 5-50 = Natural convection 50-250 = Forced convection
12	A_{cell}	441	cm^2	Cross sectional area of cell
13	t_{cell}	1	cm	Thickness of cell, cm
RTCTMODE = 2:				
11	h_{air}	40	$W/m^2{\cdot}K$	Heat transfer coefficient to ambient air 5-50 = Natural convection 50-250 = Forced convection
12	h_{PEM}	15.2	cm	Height of PEM
13	w_{PEM}	15.2	cm	Width of PEM
14	t_{cell}	1.0	cm	Thickness of cell
15	h_{cell}	21.0	cm	Height of cell
16	w_{cell}	21.0	cm	Width of cell
17	t_{plate}	2.0	cm	Thickness of end plate
18	h_{plate}	23.1	cm	Height of end plate
19	w_{plate}	23.1	cm	Width of end plate
20	k_{cell}	14.1	$W/m{\cdot}K$	Thermal conductivity of cell material
21	ρ_{cell}	2250	kg/m^3	Density of cell material*
22	$c_{p,cell}$	710	$J/kg{\cdot}K$	Specific heat for cell material*
23	k_{plate}	90.9	$W/m{\cdot}K$	Thermal conductivity of end plate material
24	ρ_{plate}	7850	kg/m^3	Density of end plate material*
25	$c_{p,plate}$	450	$J/kg{\cdot}K$	Specific heat for end plate material*
RTCTMODE = 3:				
11	R_t	0.06179	K/W	Thermal resistance per stack
12	C_t	32197	J/K	Thermal capacitance per stack*

Note! The parameters ρ_{cell}, $c_{p,cell}$, ρ_{plate}, $c_{p,plate}$, and C_t are dummy values in TMODE = 1.

PEMFC Geometry

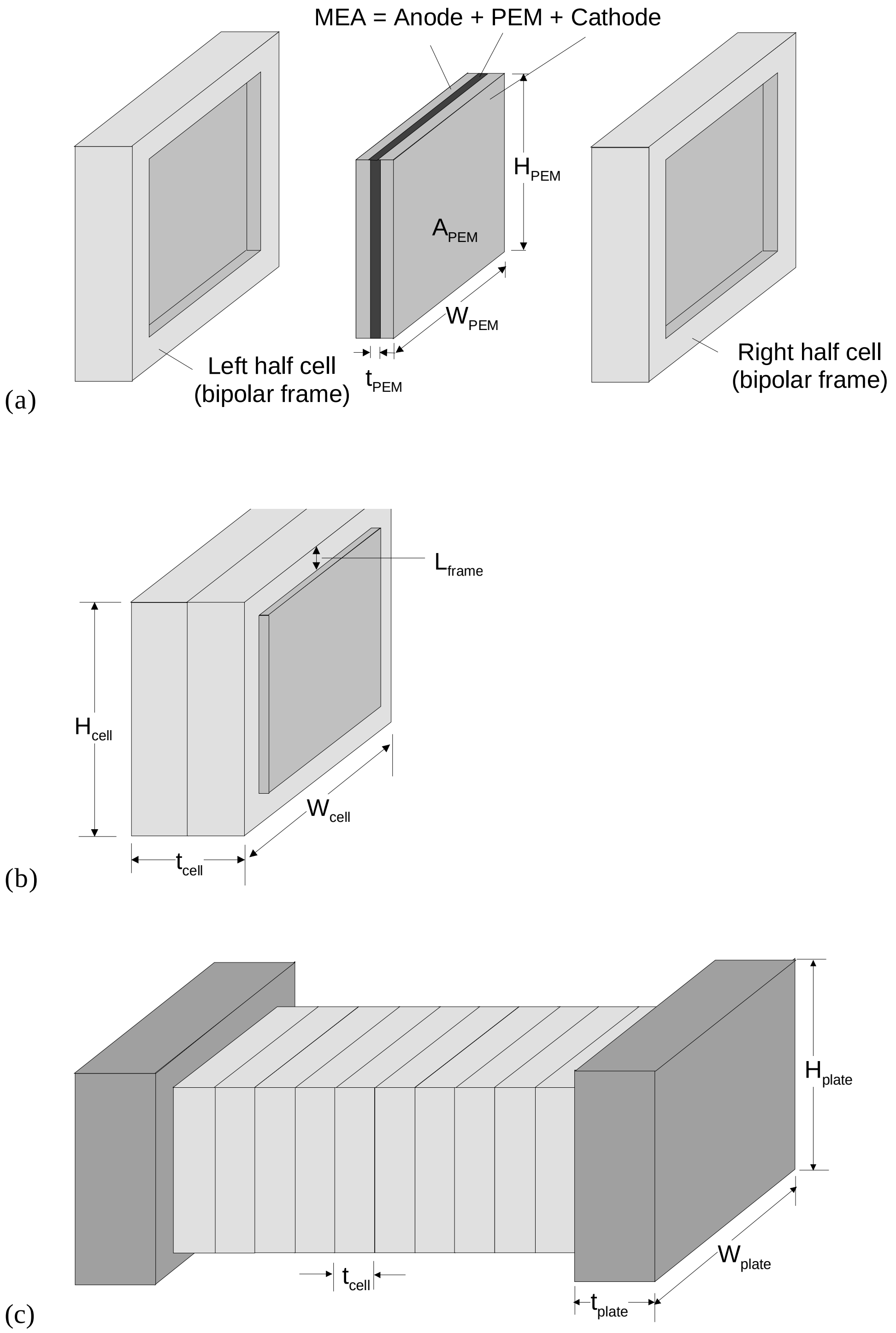

Figure 4 Different views of a PEMFC: (a) Membran Electrode Assembly (MEA) + bipolar plates, (b) Single cell, and (c) 10-cell stack + 2 end plates.

Source Code & Related Program

Table 14 TYPE170 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE170.FOR	4.0	2001.05.10
EES source code	PEMFC4.FOR	4.0	2001.05.10
EES program	PEMFCSWelcome.EES	1.0	2001.09.06

References

Amphlett J. C., Baumert R. M., Mann R. F., Peppley B. A., Roberge P. R. and Harris T. J. (1995a) Performance modelling of the Ballard Mark IV solid polymer electrolyte fuel cell. Part I - mechanistic model development. *J. Electrochem. Soc.* **142** (1), 1-8.

Amphlett J. C., Baumert R. M., Mann R. F., Peppley B. A., Roberge P. R. and Harris T. J. (1995b) Performance modelling of the Ballard Mark IV solid polymer electrolyte fuel cell. Part II - empirical model development. *J. Electrochem. Soc.* **142** (1), 9-15.

Amphlett J. C., Mann R. F., Peppley B. A., Roberge P. R., Rodrigues A. and Salvador J. P. (1996) A model predicting transient responses of proton exchange membrane fuel cells. *J. Power Sources* **61** (1-2), 183-188.

Mann R. F., Amphlett J. C., Hooper M. A. I., Jensen H. M., Peppley B. A. and Roberge P. R. (2000) Development and application of a generalised steady-state electrochemical model for a PEM fuel cell. *J. Power Sources* **86** (1-2), 173-180.

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems*. PhD thesis, Norwegian University of Science and Technology, Trondheim.

Ulleberg Ø. (2001) *Evaluation of IFE's 100 W PEM Fuel Cell Stack Performance*. Internal report, Institute for Energy Technology, N-2027, Kjeller Norway.

TYPE173

Alkaline Fuel Cell

Version 1.0

Abstract

TYPE173 is a simple mathematical model for an alkaline fuel cell (AFC). The electrochemical model is based on an empirical relationship for the current-voltage characteristic at normal operating temperature. The heat generated by the AFC-stack is calculated, but no detailed dynamic thermal model is included. TYPE173 has been modeled with a specific AFC from ZeTek in mind (Brown, 2001; ZeTek, 2001).

Overview

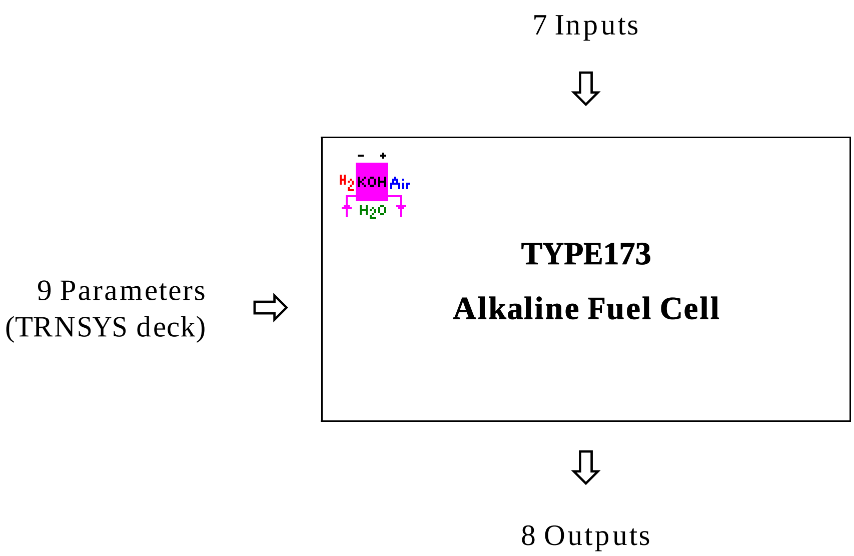

Figure 5 TYPE173 information flow

Inputs & Outputs

Table 15 TYPE173 - Inputs

#	Input	Example	Units	Description
1	γ	1	-	Switch (0 = OFF, 1 = ON)
2	I_{stack}	109	A	Total FC current
3	T_{stack}	70	°C	Average FC stack temperature
4	p_{H2}	1	bar	Hydrogen inlet pressure
OXMODE = 1:				
5	p_{Air}	1	bar	Air inlet pressure
OXMODE = 2:				
5	p_{O2}	1	bar	Oxygen inlet pressure
6	S_{H2}	1	-	Stoichiometric ratio for hydrogen
7	S_{ox}	4	-	Stoichiometric ratio for oxidant

Table 16 TYPE173 - Outputs

#	**Output**	**Units**	**Description**
1	P_{FC}	W	Total FC power output
2	U_{STACK}	V	Voltage across each stack in parallel
3	η_e	0…1	Energy effiency
4	$I_{FC,d}$	mA/cm^2	Current density
5	U_{cell}	V	Cell voltage
6	V_{H2}	Nm^3/hr	Hydrogen consumption
OXMODE = 1:			
7	V_{air}	Nm^3/hr	Air consumption
OXMODE = 2:			
7	V_{O2}	Nm^3/hr	Oxygen consumption
8	Q_{gen}	W	Heat generated by fuel cell

Parameters

Table 17 TYPE173 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	OXMODE	1	-	Type of oxidant fed to the cathode OXMODE = 1: Air OXMODE = 2: pure oxygen
2	$n_{m,ser}$	64	-	Number of FC modules in series per stack
3	$n_{s,par}$	25	-	Number of stacks in parallel per FC unit
4	A_{elec}	100	cm^2	Electrode area per cell
5	η_F	0.987	0…1	Faraday efficiency
6	U_o	5.6	V	Open-circuit voltage per cell
7	b_{tafel}	0.21727	V / dec	Tafel slope
8	R_{ohm}	0.01168	Ω	Ohmic resistance
9	$U_{c,min}$	0.4	V	Minimum allowable cell voltage

Source Code & Related Program

Table 18 TYPE173 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE173.FOR	1.0	2001.07.17
EES source code	AFC1.FOR	1.0	2001.07.16
EES program	AFC1.EES	1.0	2001.07.16

References

Brown M. (2001) Testing of ZeTek stacks. *Personal communication*, Industrial Research Limited, Christchurch, New Zealand.

ZeTek (2001) *ZeTek Mk2-4 stack specification sheet*. http://www.zevco.co.uk/, July.

TYPE160

Advanced Alkaline Electrolyzer

Version 4.0

Abstract

TYPE160 is a mathematical model for a high pressure alkaline water electrolyzer. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships. A dynamic thermal model is also included. A temperature dependent current-voltage curve for a given pressure and a Faraday efficiency relation independent of temperature and pressure form the basis of the electrochemical model. The electrolyzer temperature can be given as input, or calculated from a simple or detailed thermal model (Ulleberg, 1998; 2001).

Overview

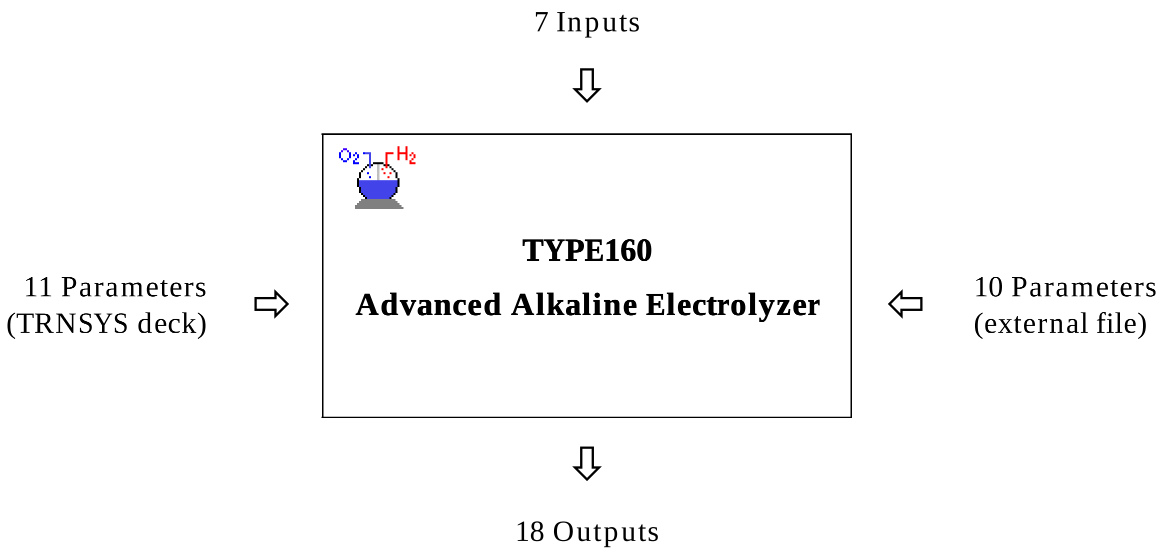

Figure 6 TYPE160 information flow

Inputs & Outputs

Table 19 TYPE160 - Inputs

#	Input	Units	Description
1	γ	-	0 = OFF, 1 = ON
2	I_{ely}	A	Electrical current (electrolyzer load)
3	p_{ely}	bar	Pressure (constant)
4	T_{amb}	°C	Ambient temperature
5	$T_{cw, in}$	°C	Cooling water inlet temperature
6	V_{cw}	Nm³/hr	Cooling water flow rate
T_{mode} = 1:			
7	T_{ely}	°C	Electrolyzer operating temperature
T_{mode} = 2 or 3:			
7	T_{ini}	°C	Initial electrolyzer temperature

Table 20 TYPE160 - Outputs

#	Output	Units	Description
1	I_{ely}	A	Electrical current (electrolyzer load)
2	U_{ely}	V	Voltage across each stack
3	P_{tot}	W	Power consumption
4	V_{H2}	Nm³/hr	Hydrogen production
5	V_{O2}	Nm³/hr	Oxygen production
6	η_{tot}	0…1	Overall efficiency
7	η_{e}	0…1	Energy efficiency
8	η_{F}	0…1	Faraday efficiency
9	Q_{gen}	W	Heat generated by electrolyzer
10	Q_{loss}	W	Heat loss to ambient
11	Q_{cool}	W	Auxiliary cooling
12	Q_{store}	W	Stored thermal energy
13	T_{ely}	°C	Electrolyzer temperature
14	$T_{cw,out}$	°C	Cooling water outlet temperature
15	$I_{density}$	mA/cm²	Current density
16	U_{cell}	V	Overall cell voltage
17	U_{rev}	V	Reversible cell voltage
18	U_{tn}	V	Thermoneutral cell voltage

Parameters

Table 21 TYPE160 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	T_{mode}		-	Temperature mode T_{mode} = 1: T_{ely} is given T_{mode} = 2: T_{ely} from simple energy balance T_{mode} = 3: T_{ely} from complex energy balance
2	Area	0.25	m^2	Area of electrodes
3	n_{cells}	21	-	Number of cells in series per stack
4	n_{stacks}	1	-	Number of stacks in parallel per unit
5	$I_{d,max}$	300	mA/cm^2	Maximum allowable operating current density
6	T_{max}	80	°C	Maximum allowable operating temperature
7	$U_{c,min}$	1.4	V	Minimum allowable operating cell voltage
8	R_t	0.167	K/W	Thermal resistance per stack*
9	τ_t	29	hr	Thermal time constant per stack*
10	ELY_{type}		-	Type of electrolyzer
11	LU		-	Logical unit for external file with parameters

Note! R_t and τ_t are only needed for T_{mode} = 2 or 3 (dummy values must be supplied for T_{mode} = 1).

Table 22 TYPE160 – Parameters (external file)

#	Parameter	Example	Units	Description
1	r_1	0.0000805	$\Omega\ m^2$	Ohmic resistance
2	r_2	-2.500E-07	$\Omega\ m^2/\ °C$	Ohmic resistance
3	s_1	0.185	V	Overvoltage on electrodes
4	t_1	-0.1002	m^2/A	Overvoltage on electrodes
5	t_2	8.424	$m^2\ °C/A$	Overvoltage on electrodes
6	t_3	247.3	$m^2\ °C^2/A$	Overvoltage on electrodes
7	a_1	250	mA/cm	Faraday efficiency
8	a_2	0.96	0…1	Faraday efficiency
9	h_1	7	W/°C	Convective heat transfer
10	h_2	0.02	W/°C per A	Conductive heat transfer

Note! Values for all 10 parameters must be listed in the external file. Only parameters r_1, s_1, t_1, a_1, and a_2 are needed in T_{mode} = 1. All parameters are needed in T_{mode} = 2 or 3.

Source Code & Related Programs

Table 23 TYPE160 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE160.FOR	4.0	2001.10.15
EES source code	ELYZER2.FOR	2.0	2001.10.15
EES program	ELYZER2.EES	2.0	2001.09.25

References

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems.* PhD thesis, Norwegian University of Science and Technology, Trondheim.

Ulleberg Ø. (2001) Modeling of advanced alkaline electrolyzers: a system simulation approach. *Int. J. Hydrogen Energy* (To be submitted for publication), Nov 2001.

TYPE164

Compressed Gas Storage

Version 3.0

Abstract

TYPE164 is a compressed gas storage model. The model calculates the pressure in the storage based on either the ideal gas law, or van der Waals equation of state for real gases (Çengel and Boles, 1989; Ulleberg, 1998).

Overview

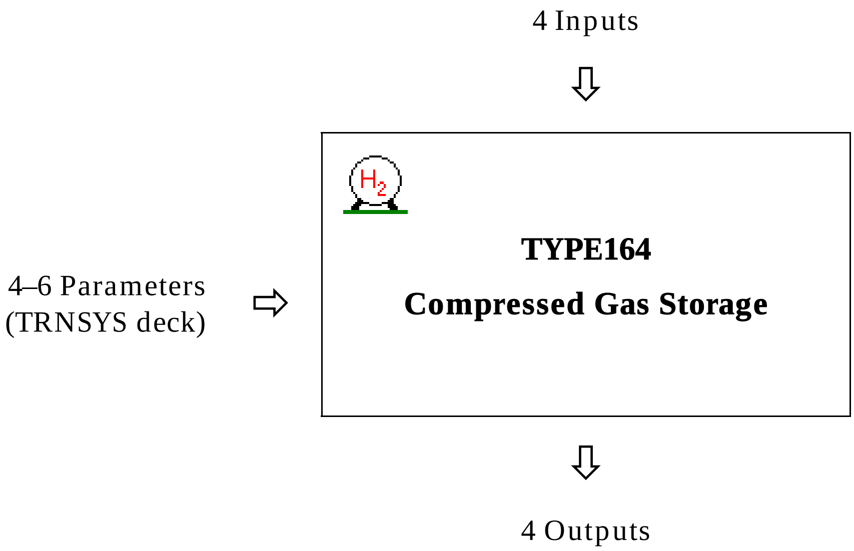

Figure 7 TYPE164 information flow

Inputs & Outputs

Table 24 TYPE164 - Inputs

#	Input	Units	Description
1	V_{in}	Nm^3/hr	Volumetric inlet flow rate
2	V_{out}	Nm^3/hr	Volumetric outlet flow rate
3	T_{gas}	°C	Temperature of gas
4	$p_{lev,ini}/p_{max}$	0…1	Initial pressure level (normalized)

Table 25 TYPE164 - Outputs

#	Output	Units	Description
1	V_{gas}	Nm^3	Volume of gas stored in tank (STP)
2	p_{gas}	bar	Pressure of gas in tank
3	$p_{lev,ini}/p_{max}$	0…1	Initial pressure level (normalized)
4	V_{dump}	Nm^3/hr	Gas dumped into atmosphere (through safety valve)

Parameters

Table 26 TYPE164 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	p_{mode}	1	-	Pressure calculation mode 1 = Ideal gas 2 = Real gas
2	p_{max}	200	bar	Rated pressure for storage vessel
3	Vol	60	m^3	Physical volume of storage vessel
4	Mol	2.0016	g/mol	Molar weight of gas
p_{mode} = 2:				
5	T_{cr}	-240.0	°C	Critical gas temperature
6	p_{cr}	12.9	bar	Critical gas pressure

Source Code & Related Programs

Table 27 TYPE164 related source code

Description	File name	Version	Date
TRNSYS source code	TYPE164.FOR	3.0	2001.07.26

References

Çengel Y. A. and Boles M. A. (1989) *Thermodynamics - An Engineering Approach*. 1 edn, McGraw-Hill, Inc., London.

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems*. PhD thesis, Norwegian University of Science and Technology, Trondheim.

TYPE185

Lead-acid Battery

Version 2.0

Abstract

TYPE185 is a quasi-static mathematical model of lead-acid battery, or Pb-accumulator. The model uses a simple equivalent circuit that relates the electrical currents, voltages, resistance (related to the concentration-overvoltage), and capacity. The main features of the model include gassing current losses, polarization effects (during charging and discharging), and calculation of equilibrium voltage at various states of charge (Saupe, 1993; Ulleberg, 1998).

Overview

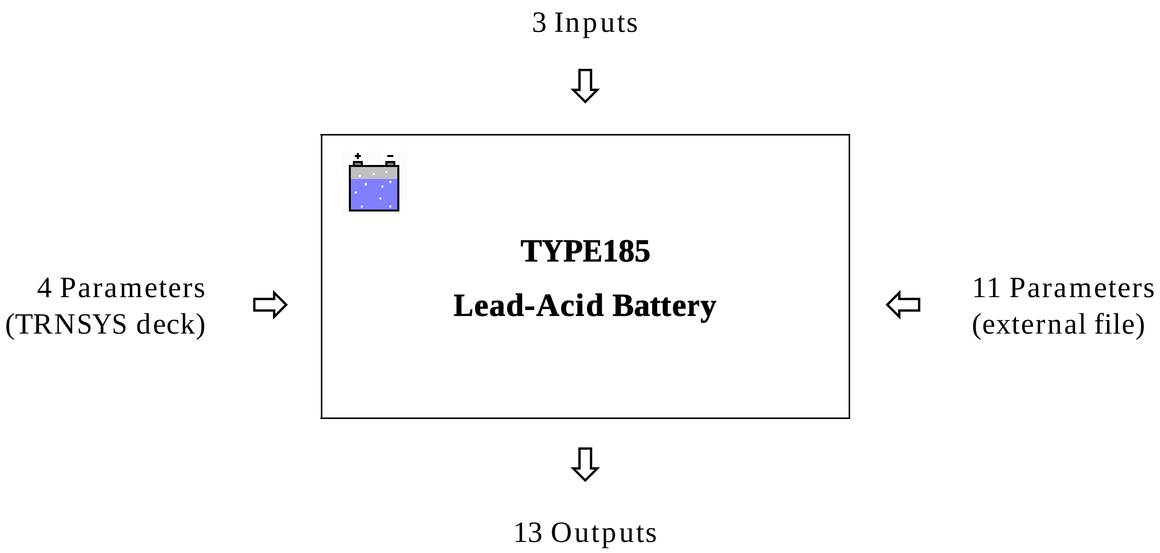

Figure 8 TYPE185 information flow

Inputs & Outputs

Table 28 TYPE185 - Inputs

#	Input	Units	Description
1	I_{bat}	A	Electrical current in / out of battery $I > 0$: Charging current $I < 0$: Discharging current
2	T_{bat}	°C	Average battery temperature
3	SOC_{ini}	%	Initial battery state of charge

Table 29 TYPE185 - Outputs

#	Output	Units	Description
1	U_{bat}	V	Voltage across battery terminals
2	SOC	%	Overall battery state of charge
3	Q_{bat}	Ah	Battery capacity
4	U_{equ}	V	Equilibrium (resting) cell voltage
5	U_{pol}	V	Polarization cell voltage
6	I_{gas}	A	Gassing current per cell
7	P_{gas}	W	Power dissipated as a result of gassing
8	I_{charge}	A	Charging current
9	P_{charge}	W	Charging power
10	$I_{discharge}$	A	Discharging current
11	$P_{sischarge}$	W	Discharging power
12	I_{dump}	A	Dumped current
13	I_{aux}	A	Auxiliary current

Parameters

Table 30 TYPE185 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	$Q_{\text{bat,nom}}$	1380	Ah	Nominal battery capacity
2	N_{cells}	110	-	Number of cells in series
3	BATTYPE	1		Type of battery
4	LU			Logical Unit for external file with battery parameters

Table 31 TYPE185 – Parameters (external file)

#	Parameter	Example	Units	Description
1	g_0	1.6e-6	-	Gassing current constant
2	g_1	0.0812	V	Gassing current constant
3	g_2	6000	K	Gassing current constant
4	$U_{\text{equ,0}}$	1.997	V	Equilibrium cell voltage at SOC = 0%
5	$U_{\text{equ,0}}$	0.1464	V / dec	Equilibrium cell voltage gradient
6	U_{ch}	5.2e-2	-	Parameter for overvoltage during charging
7	U_{dch}	-0.02703	-	Parameter for overvoltage during discharging
8	b_{dch}	0.4085	-	Discharge overvoltage constant
9	c_{dch}	0.5610	-	Discharge overvoltage constant
10	g_{100}	2.36	-	Parameter for overvoltage at SOC = 100%
11	k_{100}	53	-	Parameter for overvoltage at SOC = 100%

Source Code & Related Programs

Table 32 TYPE185 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE185.FOR	2.0	2001.02.12
EES program	Battery.EES	1.0	2001.08.29

References

Saupe G. (1993) *Photovoltaic Power Supply System with Lead-Acid Battery Storage: Analysis of the Main Problems, System Improvements, Development of a Simulation Model for a Battery (in German).* PhD thesis, University of Stuttgart, Germany.

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems*. PhD thesis, Norwegian University of Science and Technology, Trondheim.

TYPE120

Diesel Engine Generator System

Version 1.1

Abstract

TYPE120 is a mathematical model for a diesel engine generator set (DEGS). The model is based on an empirical relation (1st order polynomial) for the fuel consumption expressed as a function of the electrical power output (normalized). Electrical and fuel efficiencies are both calculated. TYPE120 can be used to predict the performance of a specific DEGS, provided a fuel consumption curve is supplied. Alternatively, a generic model can be used to predict the performance of any DEGS in the power range 5-500 kW. The generic model extrapolates from a reference fuel efficiency curve (average of 5 different DEGS). The generic model incorporates a correction factor derived from actual data measurements on DEGS for 20 remote area power systems (RAPS) with average operating powers in the range 5-186 kW (Lloyd, 1999). The default fuel is diesel (liquid), but a database with fuel properties (Adler *et al.*, 1986; McCarthy, 1982) included in TYPE120 make it possible to calculate the equivalent fuel flow rates (liquid or gas) for 5 alternative fuels: liquefied gas (LPG), propane (C_3H_8), methane (CH_4), natural gas, or hydrogen (H_2).

Overview

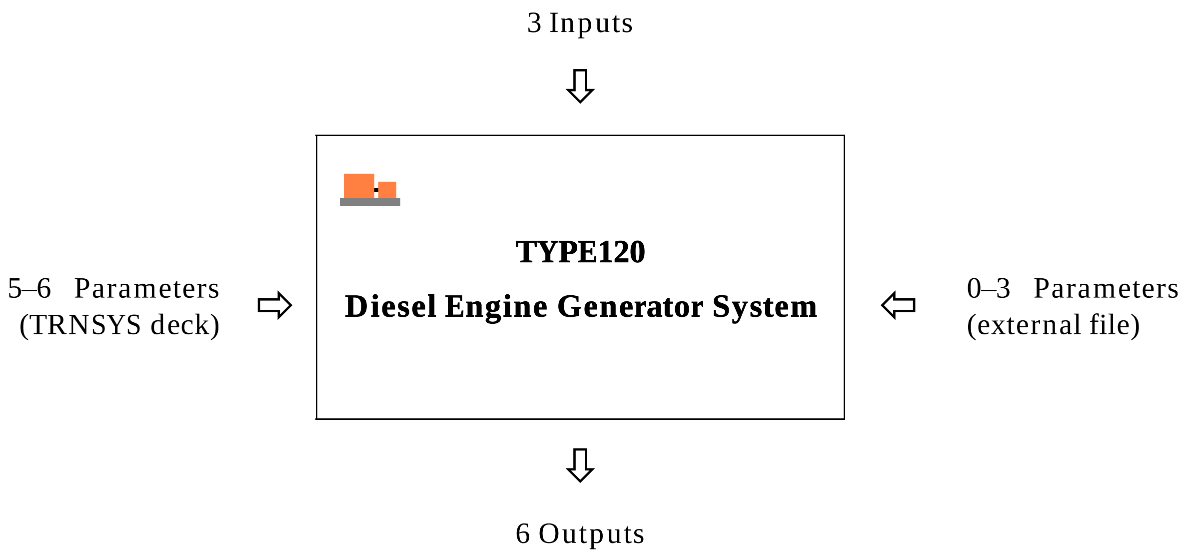

Figure 9 TYPE120 information flow

Inputs & Outputs

Table 33 TYPE120 - Inputs

#	Input	Units	Description
1	γ	-	Switch (0 = OFF, 1 = ON)
2	P_{set}	W	Power set point
3	N_{units}	-	Number of identical units in operation

Table 34 TYPE120 - Outputs

#	Output	Units	Description
1	P_{total}	W	Total power output
2	V_{liq}	L/h	Total liquid fuel consumption rate
3	V_{gas}	Nm^3/hr	Total gas fuel consumption rate (STP)
4	η_{fuel}	KWh/L	Fuel efficiency
5	η_{el}	0…1	Energy efficiency
6	Q_{waste}	W	Waste heat

Parameters

Table 35 TYPE120 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	Mode	1	-	Type of model 1 = Generic Model 2 = Specific DEGS
2	$FUEL_{TYPE}$	1	-	Type of fuel 1 = Diesel (default) 2 = Liquid petroleum gas (LPG) 3 = Propane (C_3H_8) 4 = Methane (CH_4) 5 = Natural gas (NG) 6 = Hydrogen (H_2)
3	P_{max}	360	kW	Maximum allowable power
4	P_{min}	120	kW	Minimum allowable power
Mode = 1:				
5	P_{rated}	300	kW	Rated power
Mode = 2:				
5	$DEGS_{TYPE}$	1	-	Type of DEGS
6	LUD		-	Logical unit for external file with DEGS parameters

Table 36 TYPE120 – Parameters (external file)

#	Parameter	Example	Units	Description
1	P_{rated}	40.0	kW	Rated power
2	a_{DEGS}	2.0780	L/h	1^{st} coefficient in fuel consumption curve
3	b_{DEGS}	9.2521	L/h	2^{nd} coefficient in fuel consumption curve

Source Code & Related Programs

Table 37 TYPE120 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE120.FOR	1.0	2001.08.08
EES program	DEGS2.EES	2.0	2001.08.16

References

Adler U., Bauer H., Bazlen W., Dinkler F. and Herwerth M. (Eds) (1986) *Automotive Handbook*. 2nd edn, Robert Bosch GmbH, Stuttgart.

Lloyd C. R. (1999) *Assessment of diesel use in remote area power supply*. Internal report prepared for the Australian Greenhouse Office, Energy Strategies, Canberra.

McCarthy R. D. (1982) *Mathematical models for the prediction of liquefied-natural-gas densities*. Thermophysical Properties Division, National Bureau of Standards, USA.

TYPE175

Power Conditioning

Version 6.0

Abstract

TYPE175 is a mathematical model for a power conditioning unit. The model is based on empirical efficiency curves for electrical converters (DC / DC) or inverters (DC / AC or AC / DC). The empirical relationship used in TYPE175 was first proposed by (Laukamp, 1988) and further improved by (Ulleberg, 1998).

Overview

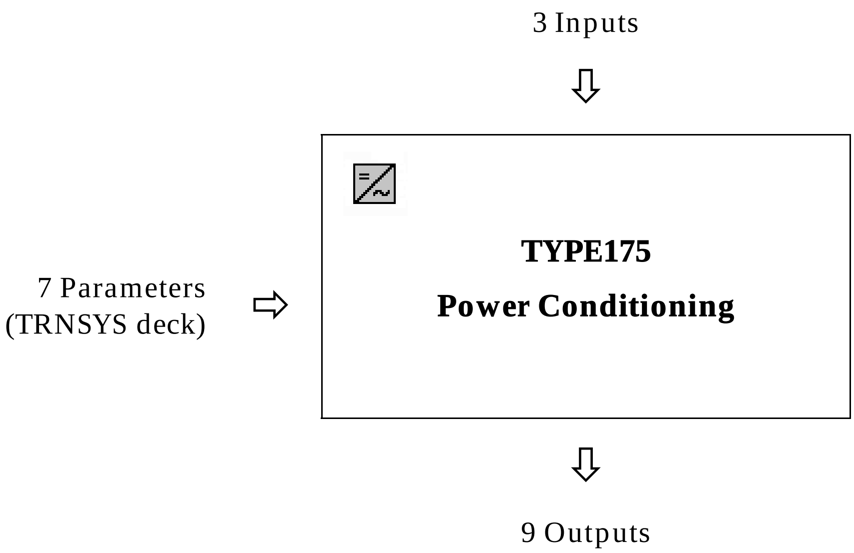

Figure 10 TYPE175 information flow

Inputs & Outputs

Table 38 TYPE175 – Inputs

#	Input	Units	Description
1	U_{in}	V	Voltage input
2	$U_{out,set}$	V	Voltage output (set point)
Mode = 1:			
3	P_{in}	W	Input power (source) is known
Mode = 2:			
3	P_{out}	W	Output power (load) is known

Table 39 TYPE175 - Outputs

#	Output	Units	Description
1	U_{out}	V	Voltage output
2	I_{out}	A	Current output
3	P_{out}	W	Power output
4	η	0…1	Efficiency
5	U_{in}	V	Voltage input
6	I_{in}	A	Current input
7	P_{in}	W	Power input
8	P_{loss}	W	Power loss
9	P_{aux}	W	Auxiliary power

Parameters

Table 40 TYPE175 – Parameters (TRNSYS deck)

#	Parameter	Example	Units	Description
1	Mode	1	-	Mode = 1: Input power (source) is known Mode = 2: Output power (load) is known
2	P_{nom}	26e3	W	Nominal power (rated power)
3	P_0 / P_{nom}	5.836e-3	-	Idling constant
4	U_s	2.06	V	Voltage set point
5	$R_i \times P_{nom}$	138.42	V^2	Ohmic constant
6	N_{units}	1	-	Number of units in parallel
7	P_{aux}	0	W	Auxiliary power

Source Code & Related Programs

Table 41 TYPE175 related source code & EES program files

Description	File name	Version	Date
TRNSYS source code	TYPE175.FOR	6.0	2001.02.12
EES program file	PowerCond.EES	1.0	2001.07.24

References

Laukamp H. (1988) *Inverter for photovoltaic systems (in German)*. User-written TRNSYS source code., Fraunhofer Institute für Solare Energiesysteme, Freiburg im Breisgau, Germany.

Ulleberg Ø. (1998) *Stand-Alone Power Systems for the Future: Optimal Design, Operation & Control of Solar-Hydrogen Energy Systems*. PhD thesis, Norwegian University of Science and Technology, Trondheim.

HYDROGEMS

Hydrogen Energy ModelS

PV	DEGS	WECS
Electrolysis	PEMFC	AFC
DC / AC	Battery	Storage