NATURAL GAS FUEL CELL BASED POWER SYSTEM FOR MUN ENGINEERING BUILDING

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OUTLINE

- **Objectives**
- **Introduction**
- **BEopt Model**
- **HOT-2000 Model**
- **Proposed Building Improvements**
- **440 kW Fuel Cell Based Power System**
- **Modeling and simulation of the fuel cell system**
- **Conclusions**

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OBJECTIVES

- To analyze MUN engineering building energy consumption
- To develop the existing engineering building model in BEopt software which shows the actual energy consumption
- To develop the existing engineering building in HOT-2000 software for validation of the BEOPT model
- To propose an improved model of the existing design in BEopt with a list of recommendations which will lead to a lower energy consumption
- To model and propose a natural gas fuel cell based power system for the improved design of MUN engineering building
- To develop a dynamic model and propose a control system for the natural gas based fuel cell system

INTRODUCTION

- MUN Engineering building is a four-storey building with a gross floor area of 25474.3 m^2
- It is facing at southeast direction

INTRODUCTION - CONT

- This engineering building annually requires about 197.9412 kWh/m^2 energy for heating and hot water [data provided by the Facilities Management Department]

- It also requires annually about 190.7 kWh/m^2 electricity for lighting and equipment [data provided by the Facilities Management Department]

- Current level of energy consumption in the Engineering building is very high. How it could be reduced?

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INTRODUCTION - CONT

- Total energy consumption in the Engineering Building (~388 kWh/m^2/year) is about 4 times more than a typical house in St. John's
- This high energy demand can be reduced by some building improvements and its CO_2 emissions could be reduced by switching to a local natural gas based fuel cell power system
- Modeling, sizing and control mechanism of the fuel cell based power system is investigated
- Proposed fuel cell based power system will provide electricity as well as heat for the building

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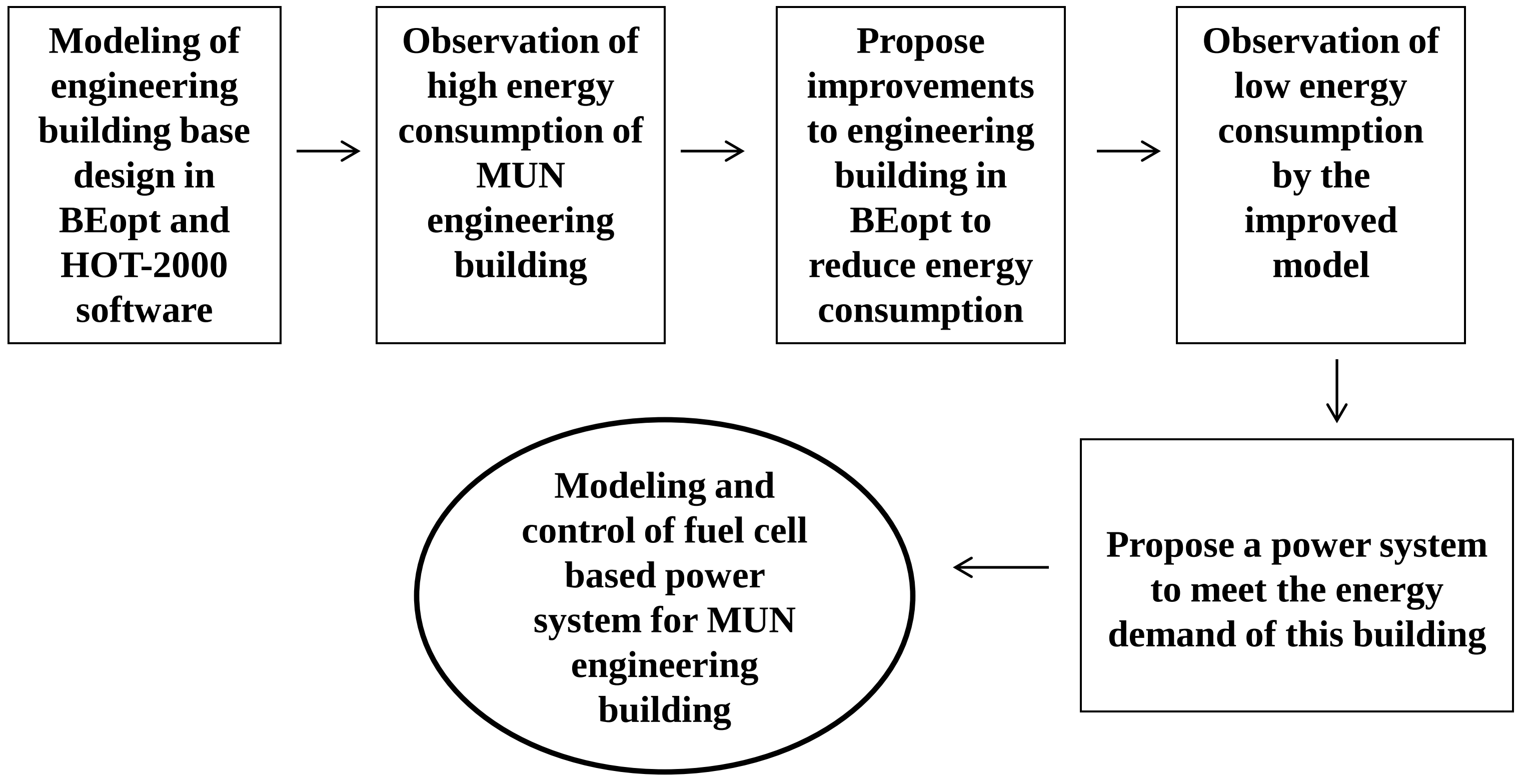
INTRODUCTION - CONT

- Steps of work done in a block diagram



BEOPT MODEL

- Firstly engineering building is modeled in BEopt (Building Energy Optimization) 2.0.0.6 software
- BEopt is developed and updated by NREL http://beopt.nrel.gov/
- In BEopt, three types of analysis i.e. design, parametric and optimization can be done
- Only design analysis is done here
- In BEopt, there are 3 types of input i.e. geometry screen, options screen and site screen

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BEOPT MODEL - CONT

a) Geometry Screen

- Each cell considered as 5 feet

- Each level is considered as 13 feet high

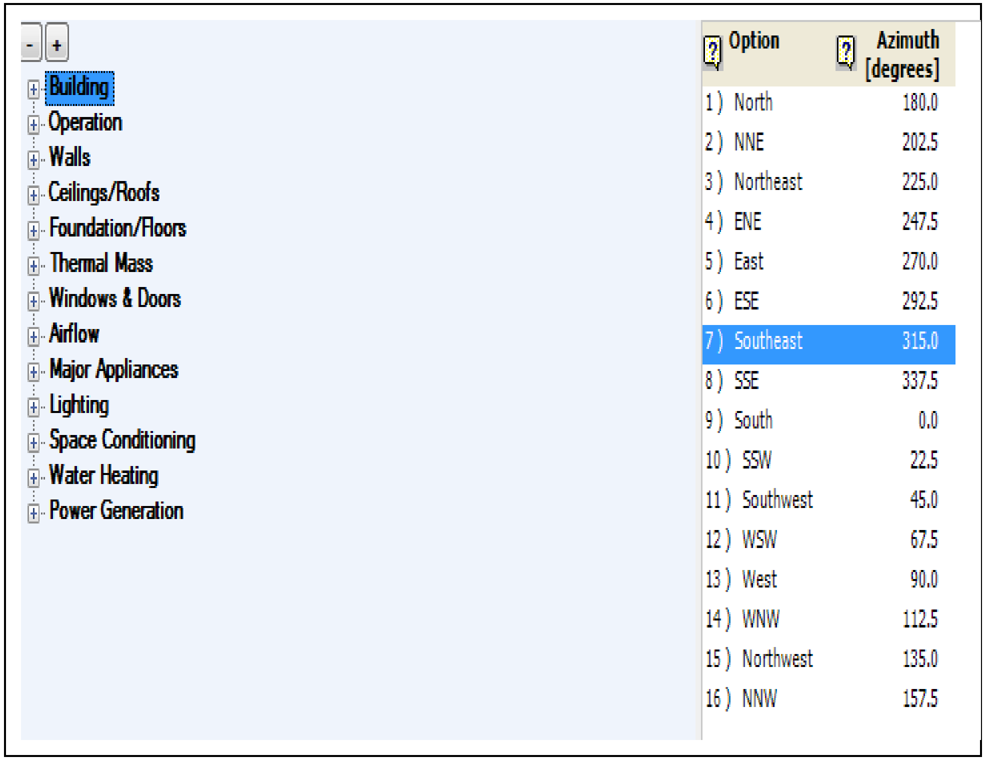
- But the third level is considered as 20 feet instead of 26 (13*2) feet because of the limitation of the software

Fig. 1 Geometry Screen of BEopt model

BEOPT MODEL - CONT

b) Options Screen

- The options screen consists of 13 options
- Each option has many sections
- If actual options are not found, new values are entered or closest options are selected



BEOPT MODEL - CONT

Table 1: Building Option Screen

Name of the Option	Selected Option
Orientation	Azimuth - Southeast 315^0
Neighbors	None

Table 2: Operation Option Screen

Name of the Option	Selected Option
Heating Set Point	71 F
Cooling Set Point	75 F
Humidity Set Point	45% RH
Miscellaneous Electric Loads	Gas/Electric-24148kWh/yr, All electric-25769kWh/yr
Miscellaneous Gas Loads	0
Miscellaneous Hot Water Loads	0
Natural Ventilation	None
Interior Shading	None

BEOPT MODEL - CONT

Table 3: Walls Option Screen

Name of the Option	Selected Option
Wood Stud	None
Double Wood Stud	None
CMU	12-in Hollow
SIP	None
ICF	None
Other	None
Wall Sheathing	None
Exterior Finish	Brick, Medium/Dark

Table 4: Ceilings/Roofs Option Screen

Name of the Option	Selected Option
Finished Roof	R-47.5 SIPs
Roof Material	Asphalt Shingles, Dark

Table 5: Foundation/Floors Option Screen

Name of the Option	Selected Option
Slab	4 feet R10 Perimeter, R5 Gap
Carpet	0% Carpet

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BEOPT MODEL - CONT

Table 6: Thermal Mass Option Screen

Name of the Option	Selected Option
Floor Mass	2 inch Gypsum Concrete
Exterior Wall Mass	Concrete
Partition Wall Mass	Concrete
Ceiling Mass	None

Table 7: Windows and Doors Option Screen

Name of the Option	Selected Option
Window Areas	15% F20 B40 L20 R20
Windows	Double-Pane, Medium-Gain Low E, Non-Metal Frame, Air Fill
Eaves	None
Overhangs	None

Table 8: Airflow Option Screen

Name of the Option	Selected Option
Air Leakage	Constant 0.1 ACH
Mechanical Ventilation	Supply

Table 9: Major Appliances Option Screen

Name of the Option	Selected Option
Refrigerator	None
Cooking Range	None
Dishwasher	None
Clothes Washer	None
Clothes Dryer	None

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BEOPT MODEL - CONT

Table 10: Lighting Option Screen

Name of the Option	Selected Option
Lighting	100% Fluorescent, Hardwired & Plug in

Table 11: Space Conditioning Option Screen

Name of the Option	Selected Option
Central Air Conditioner	None
Furnace	None
Boiler	Oil, Hot Water, Forced Draft, 85% AFUE
Electric Baseboard	None
Air Source Heat Pump	None
Ground Source Heat Pump	None
Ducts	None
Ceiling Fan	None
Dehumidifier	None

Table 12: Water Heating Option Screen

Name of the Option	Selected Option
Water Heater	Oil standard
Distribution	None
Solar Water Heating	None
SWH Azimuth	Southeast
SWH Tilt	0 degrees

Table 13: Power Generation Option Screen

Name of the Option	Selected Option
PV System	None
PV Azimuth	Southeast
PV Tilt	0 degrees

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BEOPT MODEL - CONT

c) Site Screen

- This screen allows to choose the site i.e. location of the building
- Electricity cost is entered in this way, $/kWh = 477505.65/4858059=0.0983

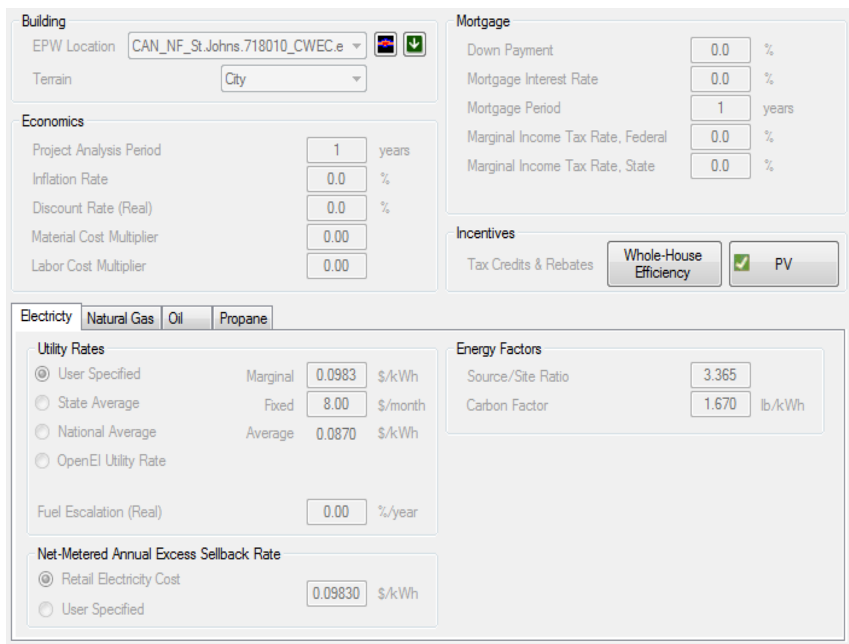

Fig. 2 Site Screen in BEOPT for electricity option

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BEOPT MODEL - CONT

- Since natural gas and propane are not used in this building, cost for these options are kept as zero
- Oil cost is entered in this way, $659935.06/(17210/0.141)gal = $5.4068/gal)

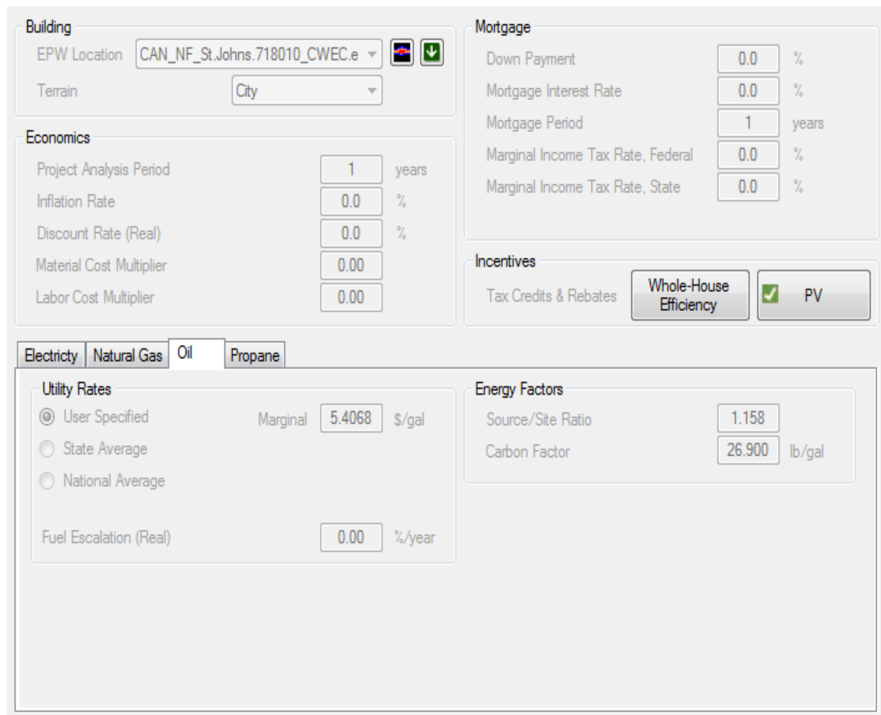

Fig. 3 Site Screen in BEOPT for oil option

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BEOPT MODEL - CONT

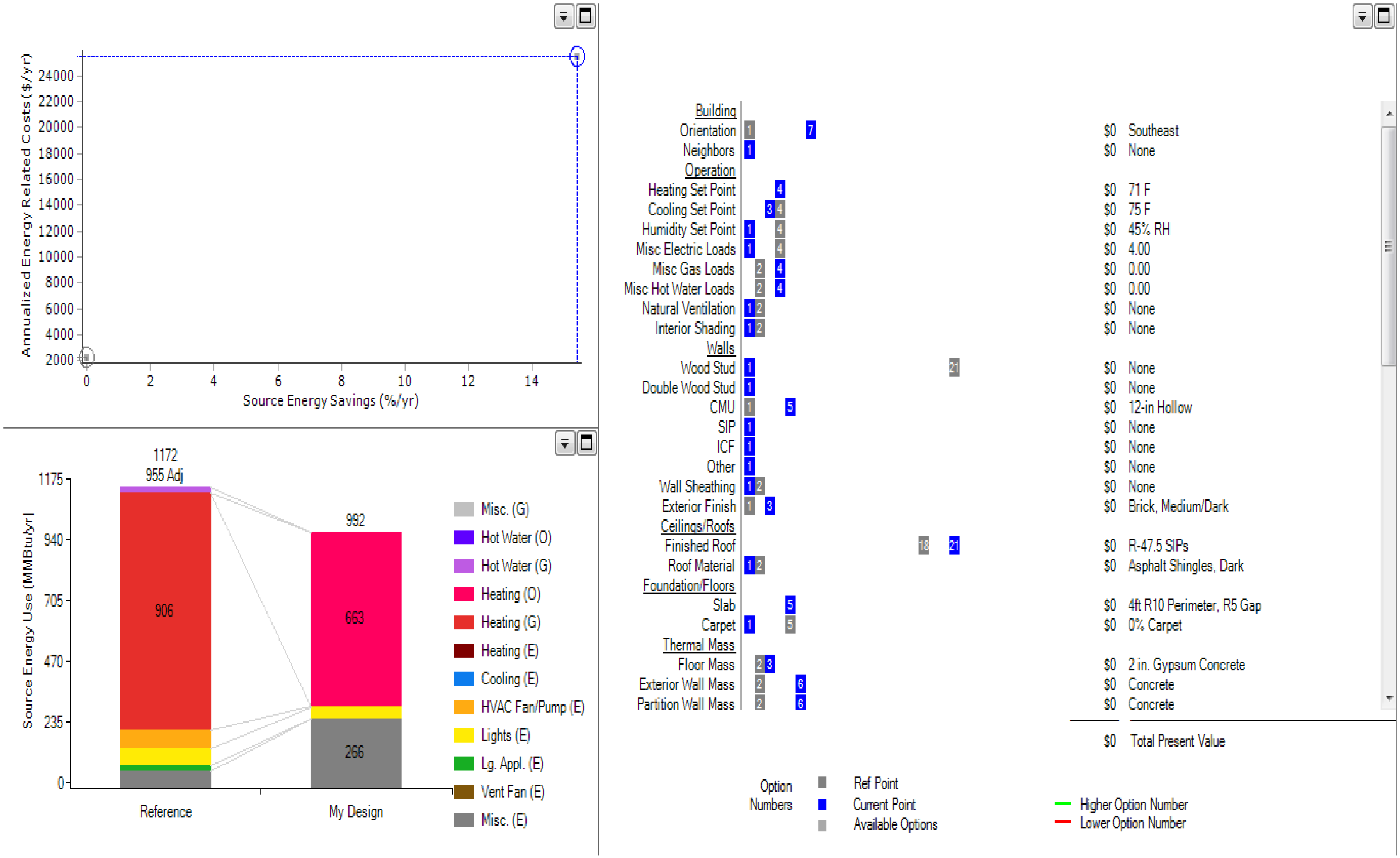

Fig. 4 Total Output Screen for actual model

BEOPT MODEL - CONT

- A smaller size scaled building is simulated in BEopt
- The outputs have to be scaled to correlate with logged data by scaling factors
- Annualized energy related cost $25,000 is 45 times less than the provided data (1137440.17/25000 = 45.5)
- The scaling factor 27 is obtained by calculation of building volume (3191057/118215=27)
- The scaling factor 33.7 is obtained by calculation of floor area (276044.3/8177=33.7)
- The scaling factor is 8 by calculation of surface floor area (290913.6 ft^2/37620 ft^2=7.73)

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BEOPT MODEL - CONT

- Electricity consumption in the scaled simulated building is (992-663=325 MMBTU * 293.1) 95257.5 kWh/yr which is (4858059/95257.5) 50 times less than the provided data

- Oil consumption is 663 MMBTU/year which is (17210/663) 26 times less than the provided data

- But the total cost factor 45 is not close to the area and volume factors (because it includes both electricity and oil costs)
- Using the scaling factor BEopt was able to simulate the MUN Engineering Building

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HOT-2000 MODEL

- HOT-2000 is developed by NRCan. Building is divided into 26 regions for simulation in HOT2000. Results are compared with the logged data.

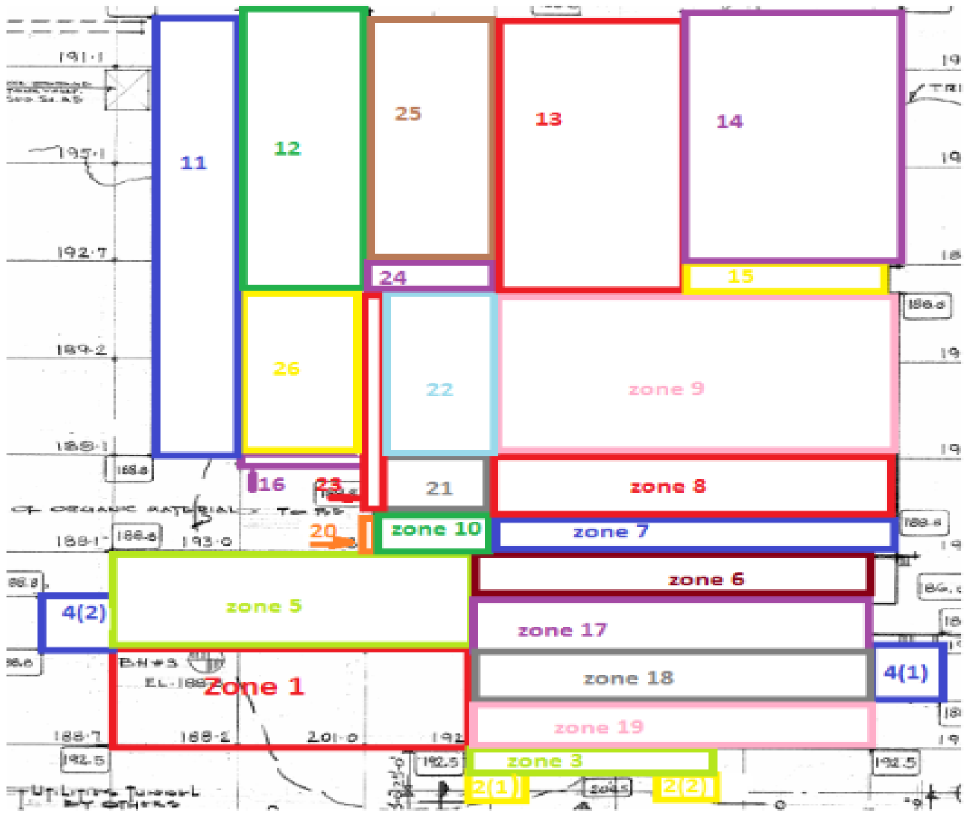
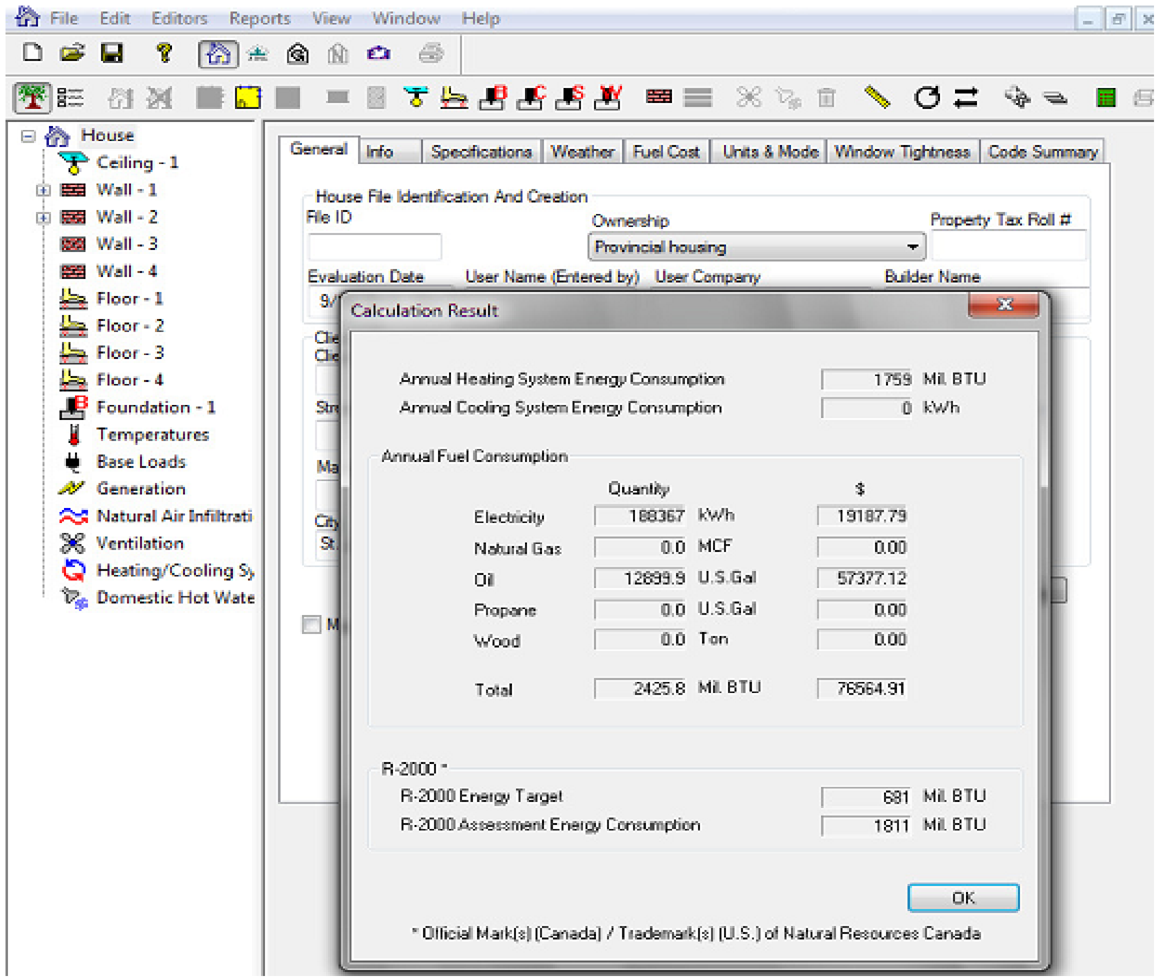


Fig. 5 Top view of engineering building with 26 regions

HOT-2000 MODEL-CONT

- As building is divided into 26 regions for simulation in HOT-2000. Results of all regions are added and compared with the logged data.



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HOT MODEL - CONT

Table 14: Simulation Results of Models in HOT-2000

Zone No.	Electrical Consumption (kWh)	Heating Consumption (MMBTU)	Zone No.	Electrical Consumption (kWh)	Heating Consumption (MMBTU)
1	188367	1759	13	356039	1586
2(1)	10362	188	14	376261	1361
2(2)	18997	162	15	57158	349
3	55169	769	16	10691	141
4(1)	31547	397	17	170856	1234
4(2)	31547	397	18	170764	1214
5	377361	1424	19	141679	1087
6	146030	1081	20	5057	99
7	109135	763	21	62063	519
8	214933	1132	22	137353	1004
9	390530	1921	23	21667	476
10	37544	353	24	29299	274
11	263580	1268	25	255874	1244
12	243370	1026	26	130411	585
Total				4043644	23813

4858059

17210

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PROPOSED IMPROVED MODEL

- How to reduce energy consumption in the building?
- The improved model of engineering building is also done in BEopt software
- Only the options screen is changed from the previous design

Table 15: Operation Option Screen

Name of the Option	Selected Option
Heating Set Point	68 F
Cooling Set Point	80 F
Humidity Set Point	45% RH
Miscellaneous Electric Loads	Gas/Electric-24148kWh/yr, All electric-25769kWh/yr
Miscellaneous Gas Loads	0
Miscellaneous Hot Water Loads	0
Natural Ventilation	None
Interior Shading	None

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PROPOSED IMPROVED MODEL - CONT

Table 16: Ceilings/Roofs Option Screen

Name of the Option	Selected Option
Finished Roof	R-49 Fiberglass, 2×12, R-25 XPS (R-value:73)
Roof Material	Metal, Dark

Table 17: Windows and Doors Option Screen

Name of the Option	Selected Option
Window Areas	12% F25 B25 L25 R25
Windows	Triple-Pane, High-Gain Low E, Insulated Frame, Air Fill
Eaves	None
Overhangs	None

Table 18: Airflow Option Screen

Name of the Option	Selected Option
Air Leakage	None
Mechanical Ventilation	HRV, 70%, 50% of ASHRAE 62.2

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PROPOSED IMPROVED MODEL - CONT

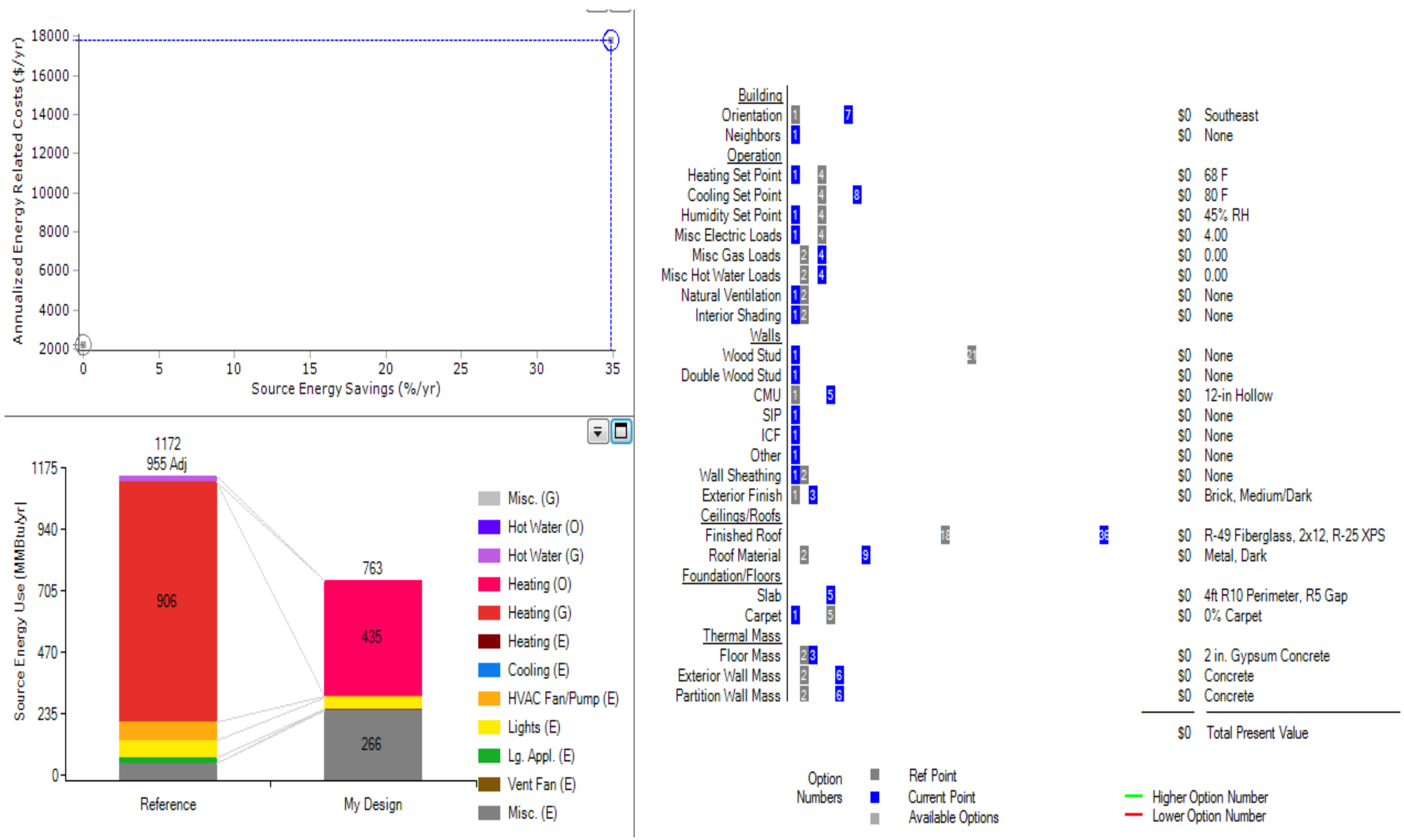

Fig. 6 Total Output Screen for improved model

PROPOSED IMPROVED MODEL - CONT

Simulation results indicate the following:

- With a better wall insulation, new windows, lower heating set point and a HRV system can improve the existing design
- The total cost can be reduced from $25000 to $17000
- The oil consumption could be reduced from 663 MMBTU to 435 MMBTU
- The electricity consumption is almost the same because it was already in a good range
- If the engineering building is modified as suggested in the improved BEopt model, it can be powered by a 440 kW natural gas based fuel cell system

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SELECTED FUEL CELL SYSTEM

MODEL 400
PureCell® System

Introducing a new generation of fuel cell technology:

The PureCell® Model 400 Energy Solution.

UTC Power
A United Technologies Company

UTC Power is a world leader in developing and producing fuel cells for on-site power, transportation, space and defense applications. UTC Power, a United Technologies Corp. company, is the only fuel cell manufacturer with experience in all five major fuel cell technologies – alkaline, proton exchange membrane, solid oxide, molten carbonate and phosphoric acid. With more than 300 stationary fuel cell units installed, we are committed to providing customers with distributed energy solutions that increase energy productivity and reliability and reduce operational costs.

The PureCell® Model 400 system is the stationary fuel cell energy solution for the commercial marketplace. The ultra clean and quiet Model 400 uses proven phosphoric acid technology, which offers the optimum blend of system performance and durability. The Model 400 can provide up to 400 kW of assured electrical power, plus approximately 1.5 million Btu/hour (450 kW) of heat, for combined heat and power applications. With an unmatched 10-year stack life and total energy efficiencies more than double those of traditional power sources, the Model 400 is an energy solution that will help save money, shield operations from interruption and secure environmentally sustainable business practices.

Performance Characteristics*

Power

Electric power	400 kW/471 kVA
Voltage/frequency	480VAC/60 Hz/3 phase

Efficiency

Electrical (LHV)	42%
Overall (LHV)	90% with full heat recovery

Fuel

Supply	Natural gas
Consumption (HHV)	3.61 MMBtu/hr (1,058 kW)
Inlet pressure	10 to 14 in. water (2.5 to 3.5 kPa)

Heat Recovery

Low grade up to (140°F supply)†	0.96 MMBtu/hr (281 kW)
High grade up to (250°F supply)†	0.59 MMBtu/hr (174 kW)

Emissions**

NO_x	0.02 lb/MWh (0.009 kg/MWh)
CO	0.02 lb/MWh (0.009 kg/MWh)
CO_2	1,050 lb/MWh (477 kg/MWh) with no heat recovery 487 lb/MWh (221 kg/MWh) with full heat recovery
SO_x	Negligible
Particulate matter	Negligible
VOCs	0.02 lb/MWh (0.009 kg/MWh)

Water

Consumption	None (up to 85°F (30°C) ambient)
Discharge	None (normal operating conditions)

Other

Noise	<65 dBA at 33 ft (10m) with no heat recovery <60 dBA at 33 ft (10m) with full heat recovery
Operating life	20 yr
Overhaul interval	10 yr
Ambient operating temperature	-20°F to 113°F (-29°C to 45°C)

PureCell
energy
Reinvented

This document contains no technical information subject to U.S. Export Regulations.

*Average performance during 1st year of operation. Refer to the Product Data and Applications Guide for additional performance characteristics. **Certified to 2007 California Air Resources Board standards. †Low-grade heat assumes a return temperature of 80°F (27°C) or lower; high-grade heat assumes a return temperature of 200°F (93°C) or lower.

MODEL 400
PureCell® System

FUEL CELL BASED SYSTEM

- If output of the fuel cell system is assumed as 400 kW, then 400*8765=3506000kWh=3506000/293.1 MMBTU =11961.8 MMBTU
- If the scaling factor considered as 30, then fuel cell need to supply a maximum of (11961.8/30=) 398 MMBTU electricity which is higher than power required as indicated in the improved design (325 MMBTU)
- For heating, fuel cell can supply (0.96+0.59=1.55 MMBTU/hr =>(1.55/30) MMBTU/h =>0.0517*8765 MMBTU/yr maximum or 452.86 MMBTU which is also higher than 435 MMBTU (consumed heat by the improved design)
- Currently, NL off-shore natural gas is not used
- We get oil for our use (MUN heating) from Middle-east

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440 KW FUEL CELL BASED POWER SYSTEM

- Fuel cell converts chemical energy into electrical energy
- Five major types of fuel cells such as AFC, PAFC, MCFC, SOFC and PEMFC
- Fuel cells are connected in series in a fuel stack
- The 440 kW fuel cell based power system is modeled in Matlab/Simulink software with its Power System Blocksets
- This model is based on empirical equations
- Four sections of the system are PAFC system, PCU, grid and control mechanism

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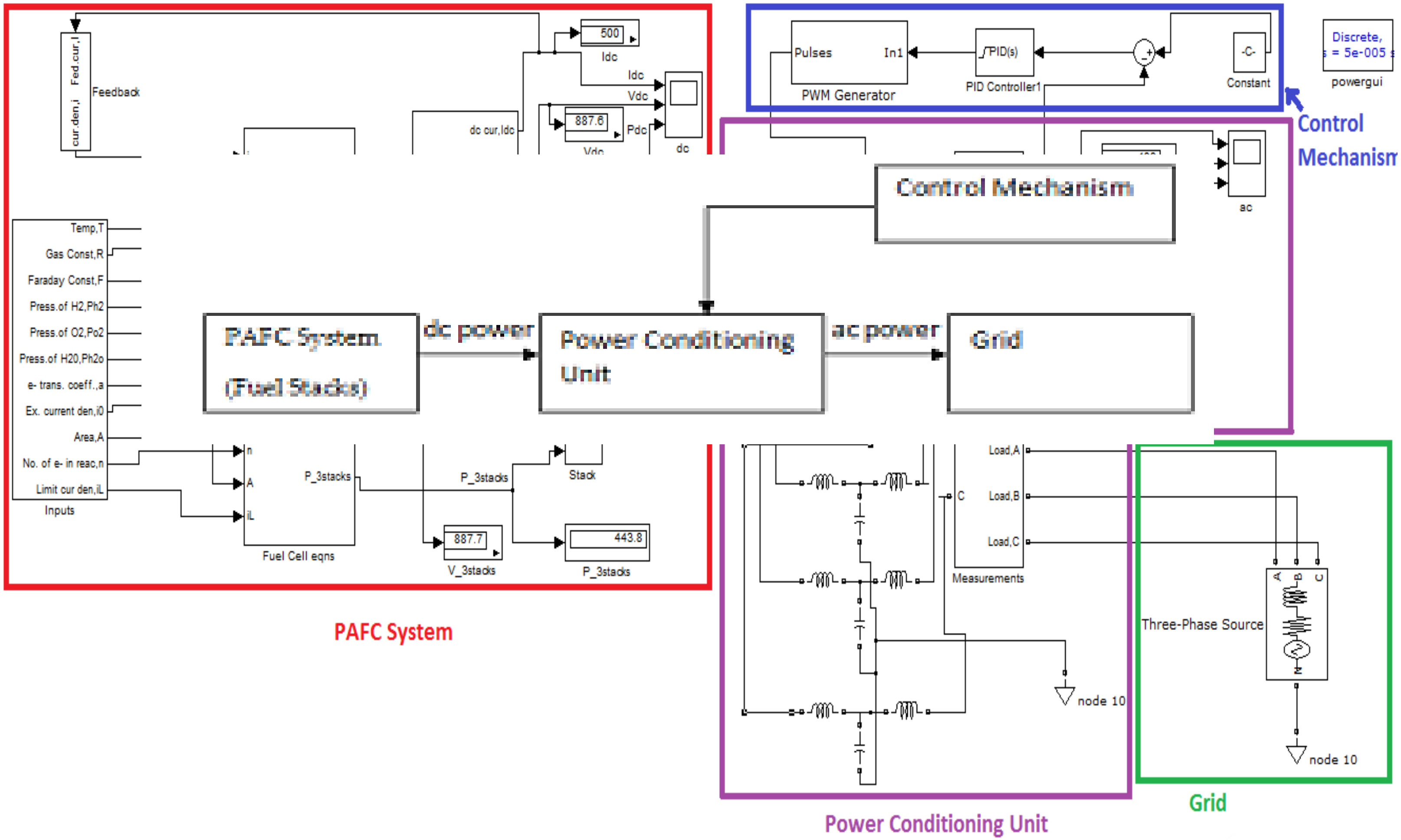
440 KW FUEL CELL BASED POWER SYSTEM - CONT



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440 KW FUEL CELL BASED POWER SYSTEM - CONT

A. PAFC System

- PAFC system section consists of ‘inputs’, ‘fuel cell equations’ and ‘connection of simulink blocks to power blocks' subsystem blocks

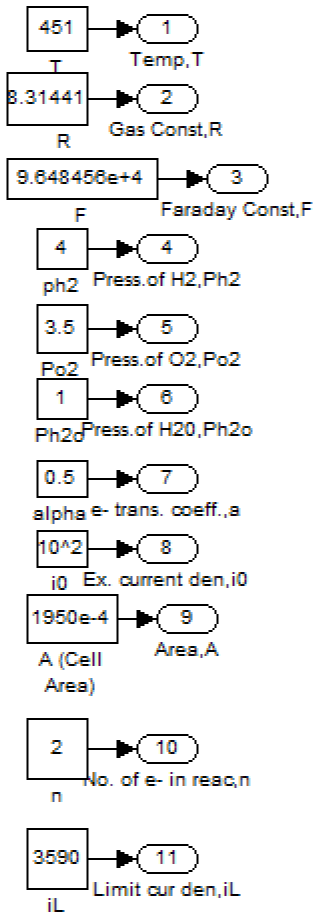

Fig. 7 'Inputs' subsystem block

Table 19: Input Parameter Values of the Proposed Model

Parameter Name	Parameter Value
Temperature, T	451 K
Gas Constant, R	8.31441 J mol^{-1} K^{-1}
Faraday Constant, F	96484.56 C mol^{-1}
Partial pressure of hydrogen, p_{H2}	4 atm
Partial pressure of oxygen, p_{O2}	3.5 atm
Partial pressure of vapor, p_{H2O}	1 atm
Electron transfer coefficient, α	0.5
Exchange current density, i_0	10^2 A m^{-2}
Cell area, A	0.1950 m^2
Number of electrons participating in the reaction, n	2
Limiting current density, i_L	3590 A m^{-2}

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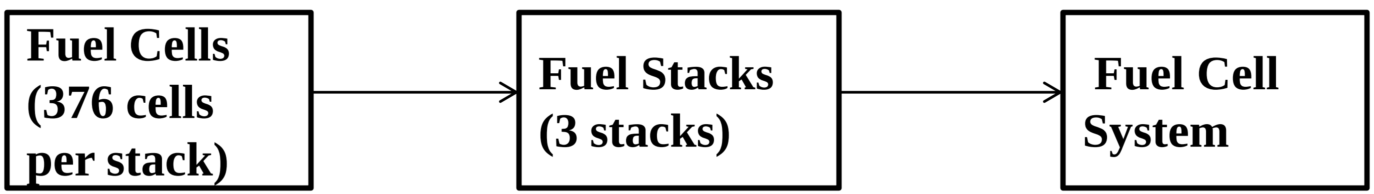
440 KW FUEL CELL BASED POWER SYSTEM - CONT

- Fuel Cell (FC) equations subsystem block contains all equations which indicates the mathematical modeling of FC
- The overview of this mathematical modeling can be observed in the following block diagram:



440 KW FUEL CELL BASED POWER SYSTEM - CONT

Nernst Potential , E_{nernst} + Activation Loss , V_{act} + Ohmic Loss, V_{ohmic} + Concentration Loss, V_{conc} = Cell Output Voltage, V_{cell}

Nernst Potential , E_{nernst} = Standard Open Circuit Voltage , E^0 + $\frac{RT}{nF}\ln[\frac{p'_{H2}(p'_{O2})^{0.5}}{p'_{H2O}}]$

$$E^0 = 1.229 - 0.85e^{-3}(T - 298.15)$$

Activation Loss , V_{act} = $-\frac{RT}{\alpha nF}\ln\frac{i}{i_0}$

Ohmic Loss, V_{ohmic} = − Electrical Current, I × Internal Resistance, R_{int}

Concentration Loss, V_{conc} = $\frac{RT}{nF}\ln\left(1-\frac{i}{i_L}\right)$

Stack Output Voltage, V_{stack} = Number of cells in a stack, N=376 × Cell Output Voltage, V_{cell}

System Output Voltage, V_{system} = Number of stacks in the system (3) × Stack Output Voltage, V_{stack}

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440 KW FUEL CELL BASED POWER SYSTEM-CONT

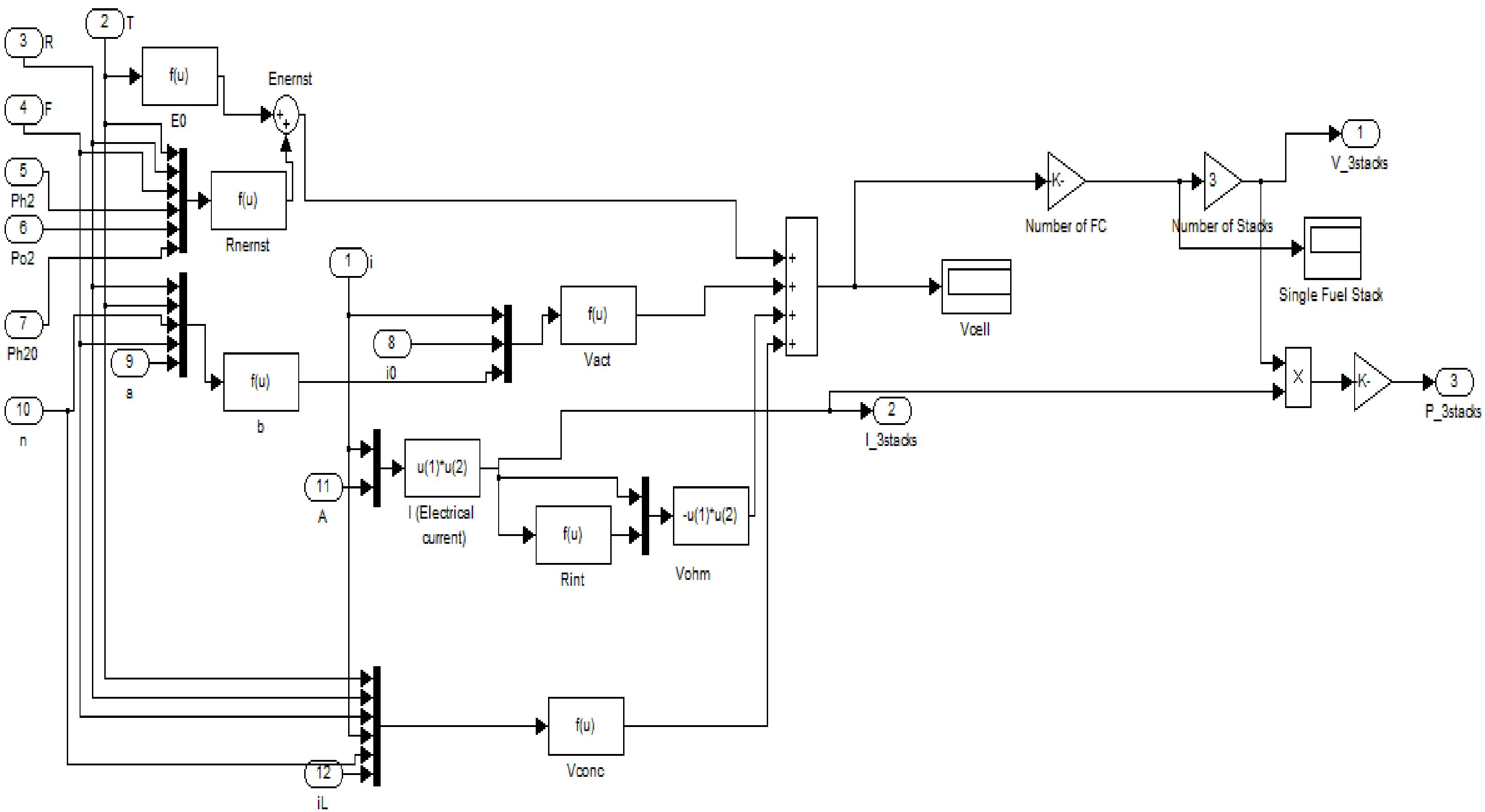

Fig. 8 'Fuel Cell equations' subsystem block

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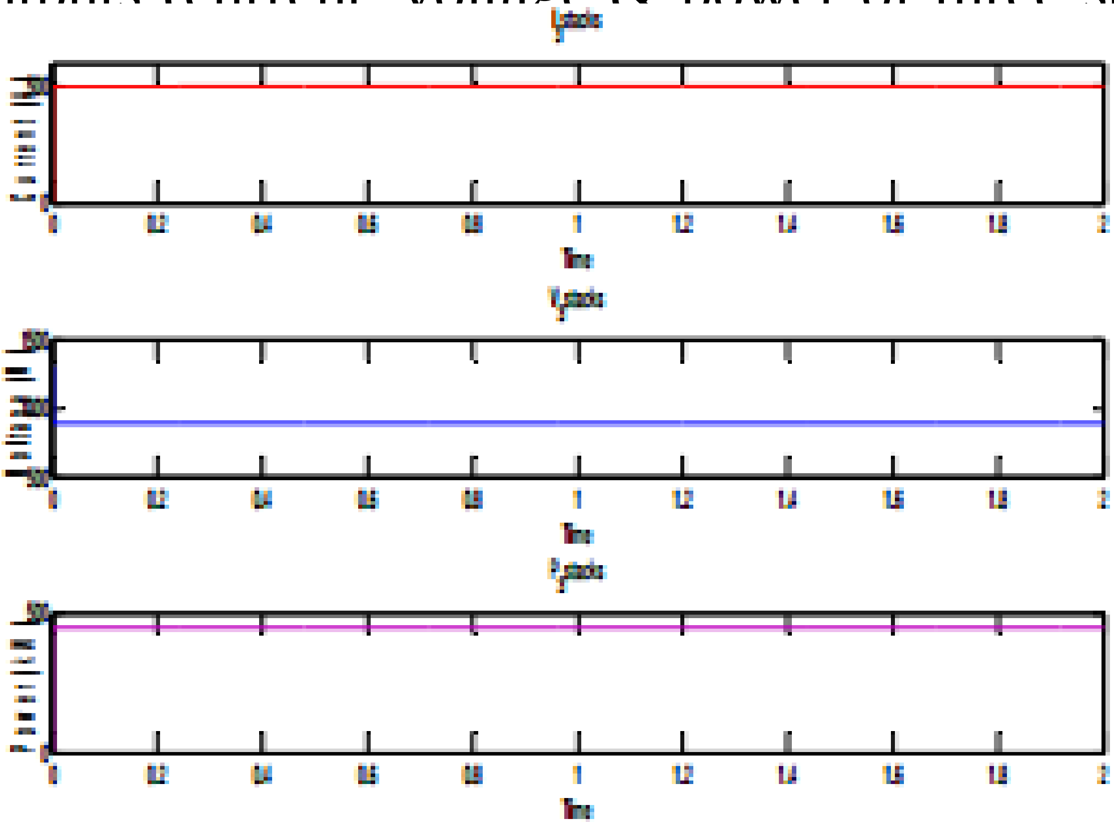
440 KW FUEL CELL BASED POWER SYSTEM - CONT

- The outputs (current, voltage & power of three stacks) of this subsy… ay blocks
- The s… one single windo…
- The … nnection of simul…



440 KW FUEL CELL BASED POWER SYSTEM - CONT

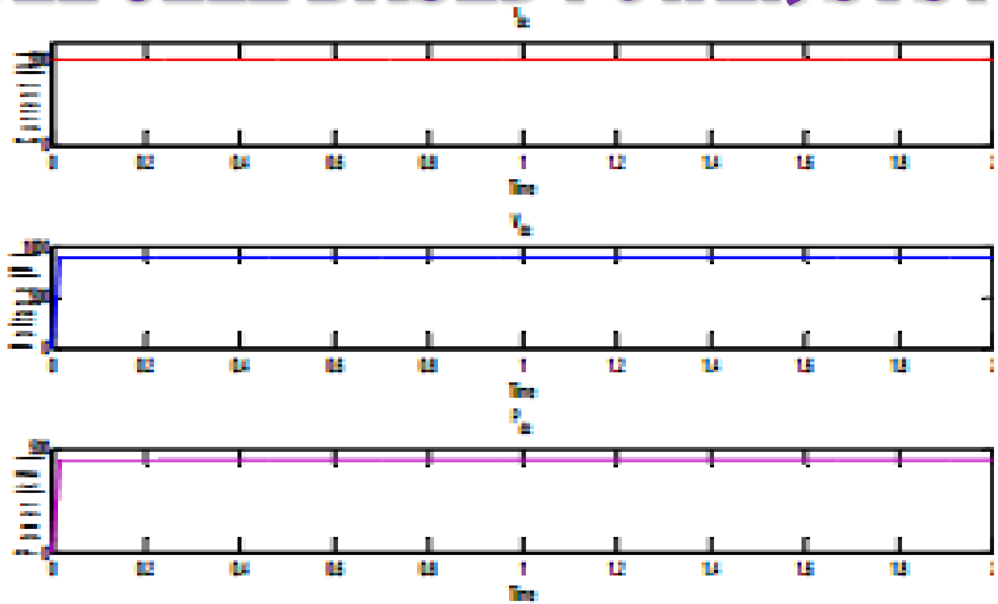


Fig. 9 Connection of simulink blocks to power blocks' subsystem block

- Fig. 9 connection between two sections i.e. red colored 'PAFC System' and purple colored 'Power Conditioning Unit'.
- The dc current from 'Connection of simulink blocks to power blocks' subsystem block to the 'Feedback' subsystem block

440 KW FUEL CELL BASED POWER SYSTEM - CONT

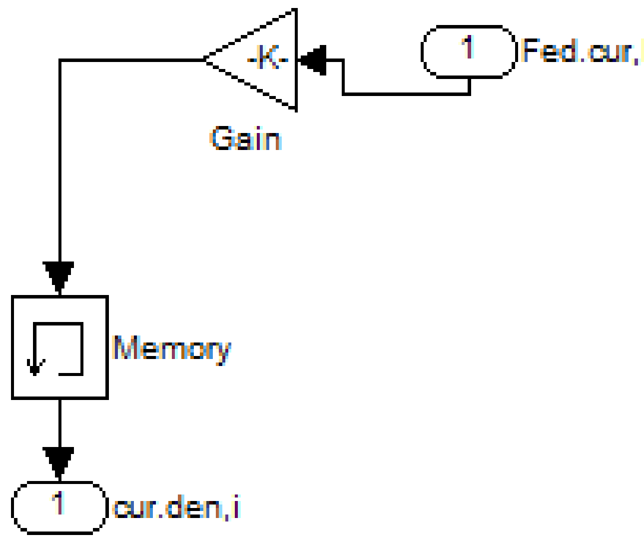
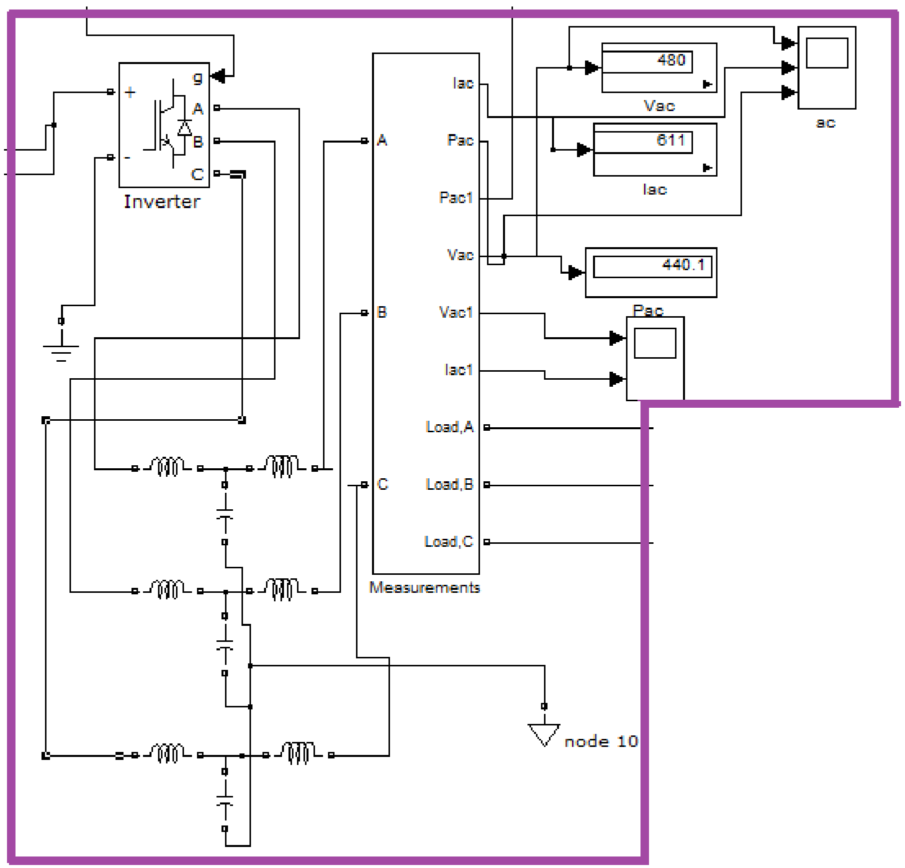


Fig. 10 'Feedback' subsystem block

- The feedback current (I) is converted into current density (i) through a gain block
- The memory block stores the initial condition

440 KW FUEL CELL BASED POWER SYSTEM - CONT

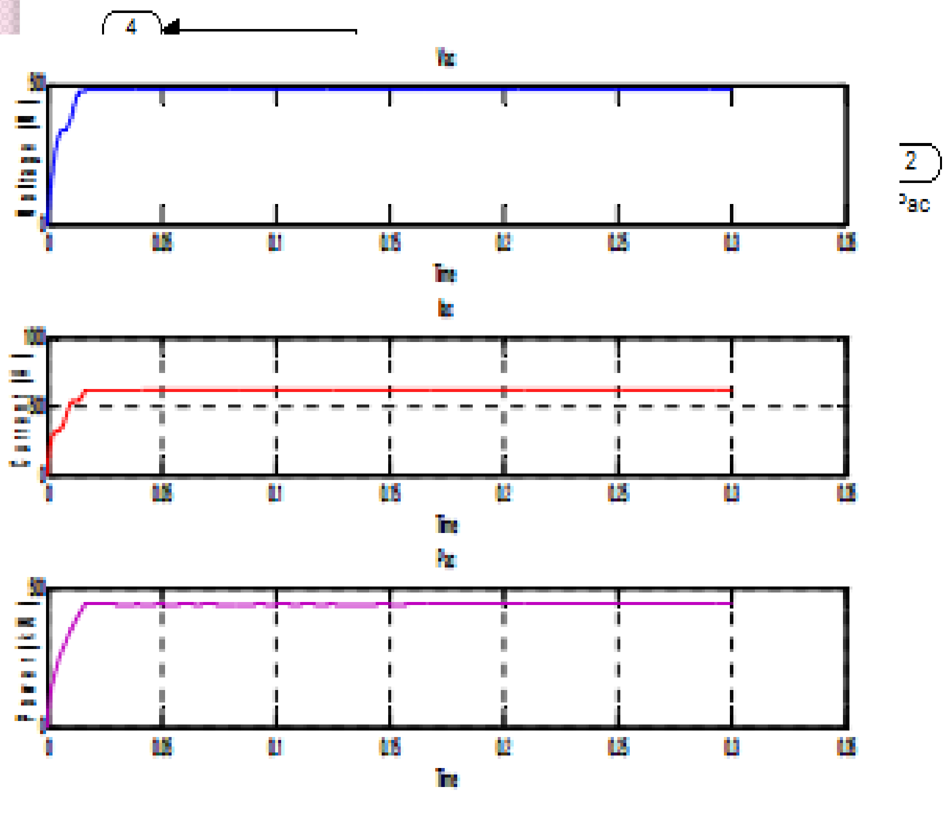
B. Power Conditioning Unit (PCU)



Power Conditioning Unit

- Contains an inverter, three LCL filters and a measurement subsystem block
- The inverter is Insulated Gate Bipolar Transistor (IGBT) type

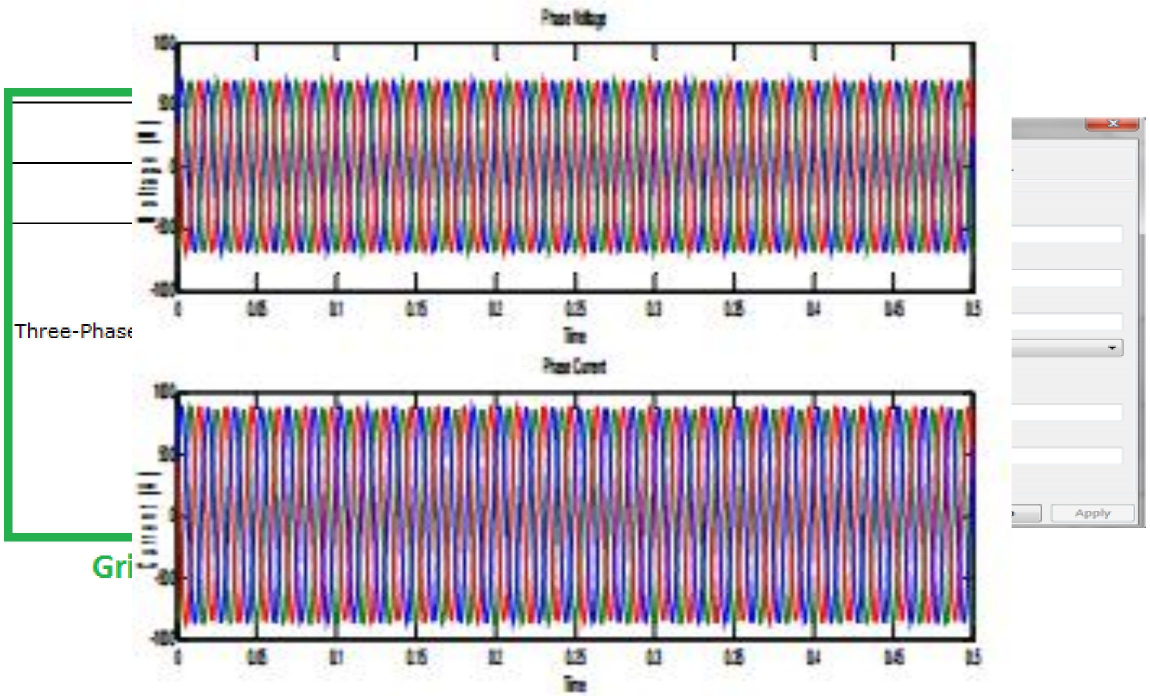
440 KW FUEL CELL BASED POWER SYSTEM - CONT



- The outputs of this PCU section are Iac, Vac& Pac
- These values can be measured through display blocks and curves can be observed through the 'ac' scope block

440 KW FUEL CELL BASED POWER SYSTEM - CONT

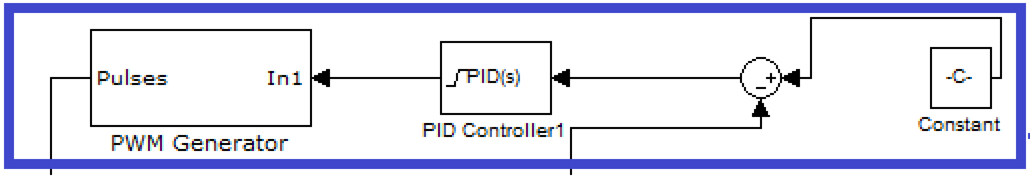
C. Grid



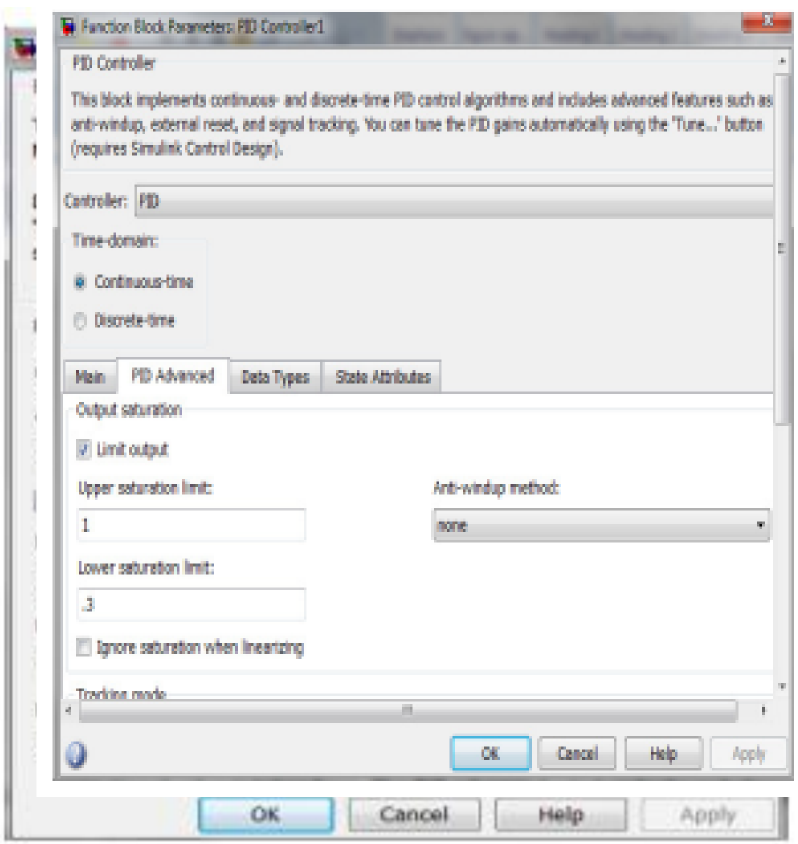
- 'node 10' neutral indicates the same neutral of PCU section
- This type of neutral is a floating type neutral without drawing the connection line between two points

440 KW FUEL CELL BASED POWER SYSTEM - CONT

D. Control Mechanism



Control Mechanism



- Consists of a PWM generator, a PID controller, a constant and a sum block
- The PWM generator gives an input (g) to the inverter which is a pure ac source

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CONCLUSIONS

- Here energy analysis of MUN engineering (commercial) building is done in BEopt and HOT-2000 software
- The impact of scaling factors is observed through a relation between simulated data and the logged data
- A number of improvements to the engineering building are proposed
- An improved model is proposed which shows lower energy consumption
- The limitations of the existing design and a list of recommendations are presented
- A model of 440 kW fuel cell based power system is developed for the improved MUN engineering building
- Power electronics system for the fuel cell is modelled and simulated
- A controller for the fuel cell is proposed and simulated

Publications

Journal Publication:

- Mahmuda Ahmed Tanni, Md Arifujjaman and M. Tariq Iqbal, "Dynamic Modeling of a Phosphoric Acid Fuel Cell (PAFC) and its Power Conditioning System", Journal of Clean Energy Technologies (JOCET), vol 1, no. 3, pp. 178-183, ISSN: 1793-821X, July 2013.
- M. A. Tanni, M. T. Iqbal, "Modeling and Control of a Grid Connected PAFC System", accepted to International Journal of Energy Science (IJES).

Conference Publication:

- M. A. Tanni, M. T. Iqbal, "Modeling and Simulation of MUN Engineering Building in BEopt and HOT-2000 softwares", Newfoundland Electrical and Computer Engineering Conference (NECEC), Canada, November 2013.
- Mahmuda Ahmed Tanni, Md Arifujjaman and M. Tariq Iqbal, "Dynamic Modeling of a Phosphoric Acid Fuel Cell (PAFC) and its Power Conditioning System", International Conference on Future Environment and Energy (ICFEE), Rome, Italy, February 2013.
- Mahmuda Ahmed Tanni, Md. Arifujjaman and M. Tariq Iqbal, "Simulink Modeling of a Phosphoric Acid Fuel Cell System", Newfoundland Electrical and Computer Engineering Conference (NECEC), Canada, November 2012.

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- Thanks to Facilities Management Department for their support and building data
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Thank you all…

Any Question?