CanadianSolar

CASSYS v. 0.9 Reference Guide

Physical Models and C# Engine Guide

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1 Introduction

The following document describes the physical models and used to develop the C#-source code available at CASSYS.

Please Note: This document is currently a work in progress.

2 General Program Flow

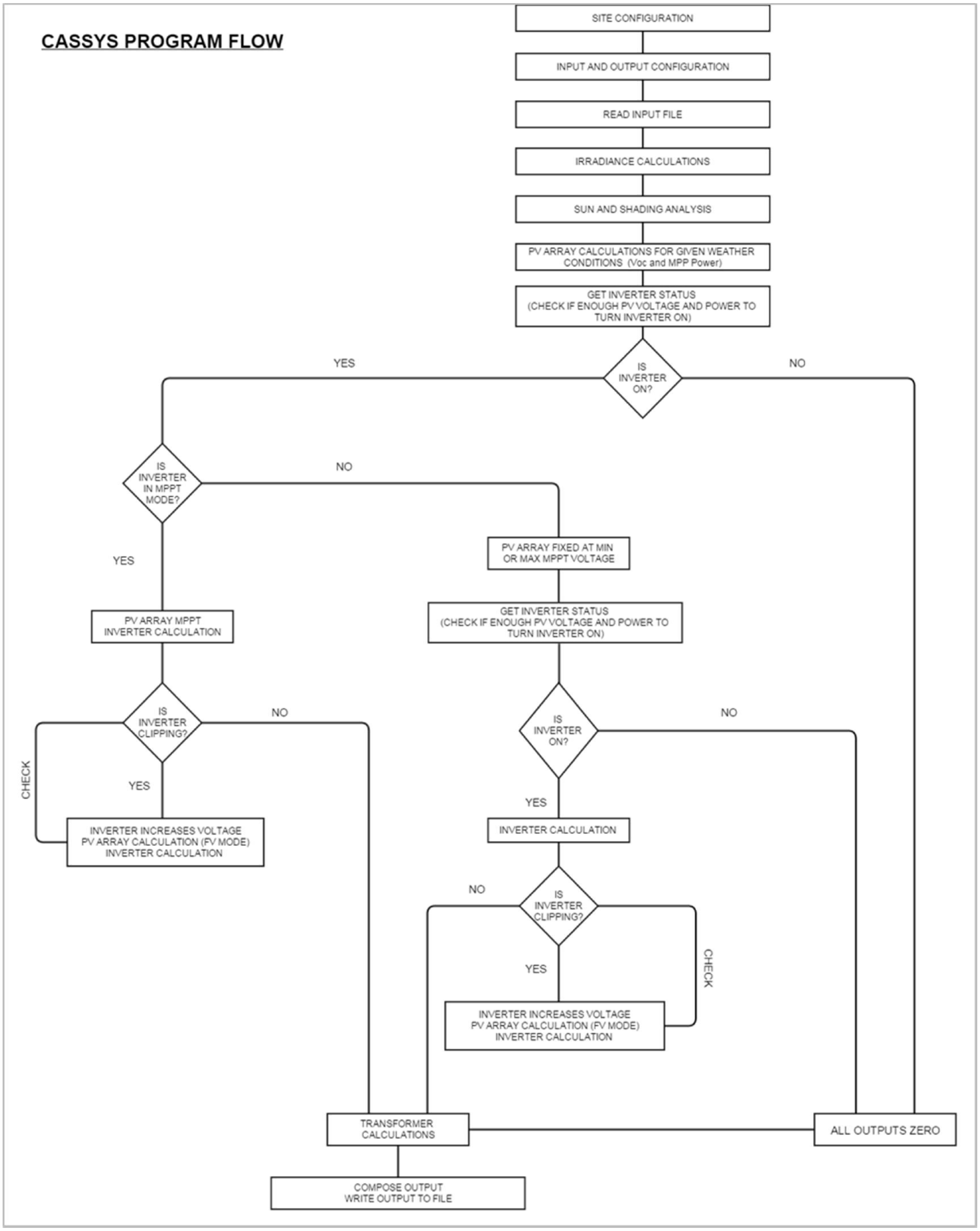

Figure 1: CASSYS v.1 Program Flow

3 List of Classes

A typical simulation flow is shown in Figure 1. Version 1.0 of CASSYS uses 16 classes to complete a simulation, and the following is a list and categorization of the classes used.

The following classes simulate physical objects or devices:

1) Inverter.cs
2) PVArray.cs
3) Shading.cs
4) Simulation.cs
5) Splitter.cs
6) Sun.cs
7) Tilter.cs
8) Transformer.cs

Classes that contain mathematical constructs:

1) Daily Astronomical Calculations: Astro.cs
2) Linear and Quadratic Interpolation: Interpolate.cs
3) Solar Radiation on a Tilted Surface: Tilt.cs

Classes that support program function, configuration and error checking:

1) Reading an Input file: MetReader.cs
2) Site and Simulation Settings: ReadFarmSettings.cs
3) Error Logging: ErrorLogger.cs
4) Batch or Interface Mode: CASSYS.cs
5) Utilities and Unit Conversions: Utilities.cs

4 Classes and Physical Model Guide

Parameters for each class are obtained from the .CSYX file which can be defined by using the CASSYS MS Excel-based interface. Parameters remain unchanged during the entirety of the simulation, and provide their relevant classes (i.e. their devices or models) key defining characteristics. The inputs are then processed and reported to an output file selected by the user. The physical models, the parameters used, and the treatment of the input values to obtain relevant outputs are discussed in this section.

4.1 Inverter *Inverter.cs*

An Inverter converts the DC power from Photovoltaic (PV) Array to AC power that would then be transferred to the grid.

4.1.1 Inputs

$DCPwr_{In}$	*Input power from the photovoltaic array*
V_{in}	*Voltage dictated by the Inverter (V)*

4.1.2 Outputs

$ACPwr_{OUT}$	*Input power from the photovoltaic array*
V_{InDC}	*Voltage dictated by the Inverter (V)*
Efficiency	*Efficiency of the Inverter*
Losses	*Losses from the Inverter (Efficiency related)*
I_{Out}	*Current produced (A, AC Single Phase)*
ACWiringLoss	*Losses due to wiring resistance between Inverter and Transformer*

4.1.3 Parameters

PNom AC	*Nominal AC Power delivered by the Inverter (can be changed to reflect de-rating)*
MPPT Tracking	*Boolean, if the inverter is currently max. power point tracking, or if the inverter is operating under fixed-voltage mode*
MPPT Window Min. Voltage	*Minimum value for MPPT (V) Window*
MPPT Window Max. Voltage	*Maximum value for MPPT (V) Window*
Num. Inverters	*Number of Inverters in the Sub-Array*
Threshold Power	*Power required to turn the Inverter ON*
Min. Voltage	*Min. DC-side voltage required to turn the Inverter ON (user defined)*
Max. Voltage	*Max. DC-voltage specification of the Inverter*
Output Voltage	*Output Voltage of the Inverter (dictated by the Grid or step-up transformer)*
OutputPhases	*Number of phases (AC) at inverter output*
Three Efficiency Curves	*Boolean, Single or Three Efficiency Curves*
Low Voltage	*Voltage threshold for low voltage efficiency curve [V]*
Med Voltage	*Voltage threshold for medium voltage efficiency curve [V]*
High Voltage	*Voltage threshold for high voltage efficiency curve [V]*

LowEff	*Jagged Array[P_{in}][P_{AC}], Low Voltage Efficiency Curve*
MedEff	*Jagged Array [P_{in}][P_{AC}], Medium Voltage Efficiency Curve*
HighEff	*Jagged Array [P_{in}][P_{AC}], High Voltage Efficiency Curve*
Single Efficiency Curve	*Jagged Array [P_{in}][P_{AC}], used if Three Efficiency Curve is false*
Nom. Output Power	*Nominal Output Power (W AC)*
Wiring Resistance	*AC wiring resistance(Ω) translated from STC % Loss*
Threshold Power	*Minimum power required to turn the Inverter ON given sufficient Voltage (Min. Voltage)*
ON	*Boolean, if the inverter is ON or OFF*
Bipolar	*Boolean, if the inverter uses bipolar inputs or not*
Clipping	*Boolean, if the inverter is currently under power limitation behaviour*

The above parameters are used to simulate the behaviour and output of the inverter. This information can be exported from an .OND file to the CASSYS database, or by using the manufacturer's datasheet in conjunction with the "Add an Inverter" button in the database (see CASSYS Interface User Manual).

4.1.4 Equations and Model Description

Inverters are responsible for the conversion of DC power into AC power that is transferred to the grid. To achieve this in a safe and controlled manner, the inverter controls the voltage of the PV array based on its operation mode. The inverter must first determine if it has sufficient voltage and power to turn on. Hence, determination of the ON or OFF state of the inverter is discussed first.

4.1.4.1 Determining ON or OFF State of the Inverter

The following flow chart (Figure 2) summarizes the process to determine if the Inverter has sufficient voltage and Power to turn ON.

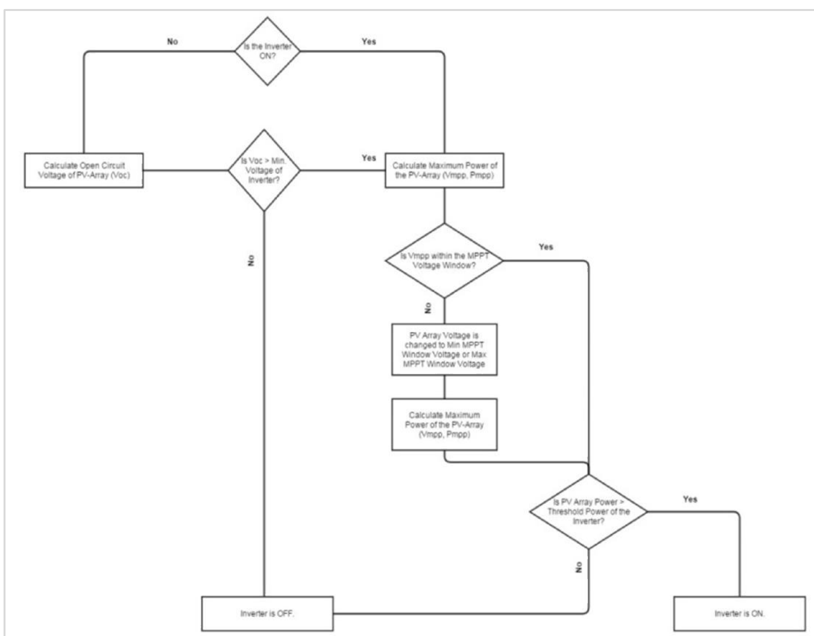

Figure 2: Determining the ON or OFF State of the Inverter

4.1.4.2 DC-Side Voltage Control

The DC-side voltage is controlled by the Inverter based on the operation mode of the Inverter. The impact on DC-side voltage for each operation mode is explained below. For all of these cases, the voltage from the array is divided by two if the inverter uses bipolar inputs.

If the Inverter is OFF

Based on the above flowchart, if the Inverter is OFF because it does not have sufficient voltage from the PV Array to turn ON (i.e. V_{OC} < Min. Voltage of Inverter) – the Inverter will report the V_{OC} as the DC-side voltage. If the Inverter has sufficient voltage to turn ON, a maximum power point tracking voltage determination is made. This is explained in the next section.

Maximum Power Point Tracking Voltage

If the Inverter has sufficient voltage to turn on, the maximum voltage (V_{MPP}) for given meteorological conditions is calculated. If the V_{MPP} is within the MPPT Voltage Window (V_{MPPmin}, V_{MPPmax}) the DC-side voltage remains at V_{MPP}. If $V_{MPPmin} < V_{MPP} < V_{MPPmax}$, the voltage of the DC-array is shifted to the V_{MPPmin} or V_{MPPmax} which is then used to calculate the power produced by the array.

Power Limiting (or Clipping) Mode

For a given input power, if the calculated output power exceeds the PNom AC of the Inverter – the limitation behaviour of the Inverter is activated. The Inverter attempts to decrease the power of the PV array to achieve an output power that does not exceed the PNom AC. To achieve this, the inverter increases the voltage of the PV Array and the corresponding efficiency is then re-calculated (as long as it does not exceed the maximum voltage of the inverter). The final voltage is then the voltage at which the Inverter limits its output to its nominal value. The voltage for which the input power is sufficiently reduced to no longer activate the power limitation mode is found using the bisection method along the PV array's Power-Voltage curve.

4.1.4.3 Modelling Efficiency

Inverter efficiency is the ratio of the AC output power (P_{OUT}) and the DC input power (P_{IN}). An inverter's efficiency varies based on input power, the DC voltage, and the inverter temperature (heat related de-rating of the inverters is commonly observed).

An efficiency curve as below is provided for some inverters based on the California Energy Commission (CEC) which was adopted from the Sandia and BEW (now DNV-KEMA) test protocol. For more information regarding the test protocol and a list of test results for various inverters, please see [1].

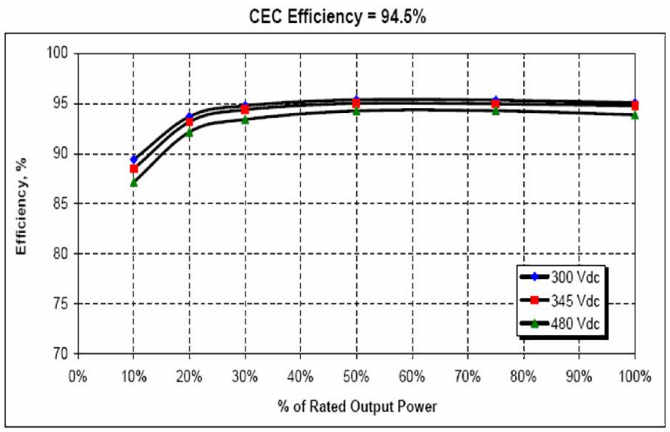

Figure 3: Voltage dependent Efficiency Curve for a sample Inverter [1]

The inverter efficiency curves used in CASSYS are defined by the efficiency measured at 8 different input power points. The inverter output is determined by using a single or a voltage-dependent (8-points each for three voltage levels: Low, Medium and High) efficiency curve based on the information available in the database.

For Single 8-point Efficiency Curve Inverters:

The curve is first translated to a $P_{OUT} = f(P_{IN})$ array using the efficiency values given. The efficiency value for a given input power is then calculated using linear interpolation (see 5.2.1.1).

For Voltage-Dependent Efficiency Curve Inverters:

For a given P_{IN}, the resultant efficiency value from the efficiency curve of each voltage level is calculated using linear interpolation similar to the previous case. This information is then used to create a voltage level vs efficiency curve (at given P_{IN}). The operating voltage of the PV array is then used as the interpolant to determine the efficiency level from the new curve using quadratic interpolation (see 5.2.1.2).

4.2 Photovoltaic Array *PVArray.cs*

The PV Array Class evaluates the performance of a solar module using the "standard" or one-diode model as described in Equations and Model Description4.2.4. The STC condition parameters for the module are obtained from module data-sheets or a PAN file. Module behaviour is calculated for a number of non-STC operating conditions such as open circuit, fixed voltage, and maximum point tracking. Values are then converted from Module to Array level and losses are applied in accordance with user input values.

4.2.1 Inputs

Shaded POA Beam Component	*Beam component of plane of array irradiance ($W{\cdot}m^{-2}$)*
Shaded POA Diffuse Component	*Diffuse component of plane of array irradiance ($W{\cdot}m^{-2}$)*
Shaded POA Ground-Reflected Component	*Ground reflected component of plane of array irradiance ($W{\cdot}m^{-2}$)*
	Angle of Incidence of the Beam Component (Radians)

Incidence Angle	Wind Speed ($m \cdot s^{-1}$) if provided by user
Wind Speed	(°C) if provided by user
Measured Module Temperature	For Soiling Percentage to be applied on irradiance
Month of the Year	

4.2.2 Outputs

Effective Global and Components of POA Irradiance	*Global, Beam, Diffuse and Ground reflected irradiance in POA after Soiling and IAM have been applied ($W \cdot m^{-2}$)*
Vout	*Voltage produced by (MPP mode) or dictated by the Inverter (Fixed-Voltage mode) of the array (V)*
Iout	*Current produced by the array under MPP or Fixed-Voltage Mode (A)*
Pout	*Power produced by the DC Array (W)*
TModule	*Temperature of the array (Calculated/Measured based, °C)*
Soiling Loss	*Power lost due to soiling of the array (W)*
Mismatch Loss	*Power lost to mismatch of module I-V curves in the array (W)*
Module Quality Loss	*Power lost to LID or aging of modules(W)*
Ohmic Losses	*Power lost to resistance in the wires from array to inverter (W)*
Nominal DC Array Power	*Power of the array under STC conditions*

4.2.3 Parameters

Due to the contextual and extensive nature of the parameters required for the modelling of the PV Array, the description of each variable is presented alongside the appropriate equation.

4.2.4 Equations and Model Description

A photovoltaic module is a non-linear DC electrical device which converts the energy of light into electricity by the photovoltaic effect. An equivalent circuit model called, the single diode model (SDM), is extensively used to determine the performance of a non-ideal solar cell under different illumination and temperature conditions. Figure 4 shows the equivalent circuit for the model.

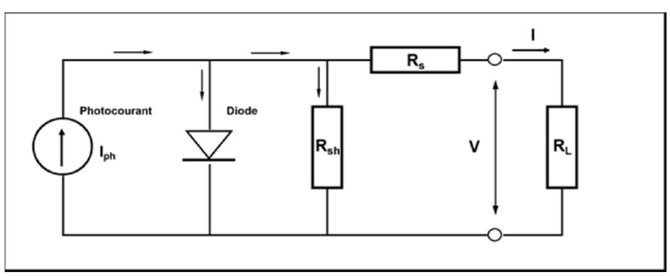

Figure 4: Equivalent circuit for the Single Diode Model (SDM) of a Solar Cell

I-V characteristics of the solar module can be completely described by equation (1).

$$I = I_\Phi - I_0 \left[e^{q\frac{(V+IR_S)}{N_{cells}\gamma k T_c}} - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad \textbf{(1)}$$

Where,

I_Φ: Photocurrent of the module [A]

I_0: Reverse saturation current of the module [A]

R_S: Series Resistance of the module [Ω]

R_{sh}: Shunt Resistance of the module [Ω]
γ: The diode ideality factor
T_c: Temperature of the cell [K]
N_{cells}: Number of cells in the module
V: Operating voltage of the module [V]
I : Current produced by the module [A]
q: Elementary Charge [C], Constant: $1.602 \text{ x } 10^{-19} C$

Parameters of the module are obtained from the module database provided as part of the user interface. For details on adding modules that are not in the database, please see the User Guide. The configuration of the panels occurs in the *void Config(..)* method, which then determines the missing parameters required to simulate array performance using the SDM equivalent circuit (see 4.2.4.1).

4.2.4.1 SDM Parameter Determination *void CalcGammaIPhiIrsRef(..)*

The first five parameters listed above depend upon the type of module selected for simulation. The only available information to determine these parameters is the I-V curve obtained under standard test conditions (STC). Since the modules do not always operate under STC conditions, the unknown parameters are solved for operation at reference conditions (lending a *Ref* subscript to each parameter).

The values for $R_{series,Ref}$ and $R_{sh,Ref}$ are obtained directly from the database included in CASSYS and can also be specified from other data sources (e.g. .PAN files for modules).

The remaining three variables $(I_{0,Ref}, I_{\Phi,Ref}, \gamma_{Ref})$ are determined by solving the SDM equation for the three known operating points of the module at STC, i.e. at open-circuit (V_{OC}, 0), at short-circuit (0, I_{SC}), and the maximum power point (V_{MPP},I_{MPP}). These yield three equations and three unknowns which are easily reduced to a function of γ_{Ref} through substitution and elimination. Once γ_{Ref} is obtained using the Newton-Raphson root-finding algorithm, it is substitute back into previous equations and a solution for each parameter $(I_{0,Ref}, I_{\Phi,Ref}, \gamma_{Ref})$ is obtained. For more details see 4.2.6.

The dependence on temperature and irradiance of each of these factors is discussed in a later section. First the determination of the effective irradiance reaching the panel, and the cell temperature model are discussed.

4.2.4.2 Effective irradiance on panel surface *void CalcEffectiveIrradiance(..)*

4.2.4.3 Incidence Angle Modifier (IAM)

The incidence angle of the beam component of the irradiance affects the amount of light reaching the cell due to reflection and refraction losses. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) proposed a convenient one parameter method of describing the efficiency of transmission for any incidence angle of incoming light [2]. This parameter (b_0) is specified by the user (based on module-specific measurements) and the Incidence Angle Modifier (IAM) is calculated using the relationship shown in (2):

$$IAM = 1 - b_0 \left(\frac{1}{\cos(IA)} - 1 \right) \quad \textbf{(2)}$$

Where,
IAM : Incidence Angle Modifier [Unitless]
b_0 : Single defining parameter for the IAM curve (ASHRAE)
IA : Incidence Angle of the Plane of Array Incidence Component (radians)

The Incidence Angle for the Plane of Array Beam Component is calculated based on the sun's position for a given time step. To see how the Incidence Angle for the Plane of Array Beam Component is calculated in detail, please see 5.3. Due to the scattered nature of the diffuse and ground-reflected components of the plane of array irradiance, an "averaged" incidence angle is used to determine the incidence angle modifier for these components. CASSYS uses the same angle of 60° to calculate IAM for the diffuse and ground-reflected components in accordance with [3].

4.2.4.4 Soiling Losses

Soiling losses account for the accumulation of dirt, snow, or sand on the panels. Users can specify values on a yearly or monthly basis. The corresponding IAM is applied to every component of plane of array irradiance and after which the user specified soiling loss percentage is applied to the resultant irradiance. This is the irradiance used in further calculations.

4.2.4.5 Effective Cell Temperature — *void CalcTemperature(..)*

Cell temperature is modelled using the equation provided below. The equation finds its basis in the Faiman Temperature Model for module temperature [4] but is modified with module adsorption and efficiency to determine the cell temperature. The equation requires an assumption regarding the adsorption of the modules which is assigned to 0.9 in the program.

$$T_c = T_a + \frac{\alpha H_{POA}(1 - \eta_{module})}{U_0 + U_1 * WS} \quad \textbf{(3)}$$

Where,
T_c : Cell temperature [°C]
T_a : Ambient air temperature [°C]
α : Adsorption coefficient of the module [default value of 0.9 is used]
H_{POA} : Incident irradiance after soiling and IAM losses are applied [W m^{-2}]
η_{module} : Efficiency of the module in the sub-array (see (4))
U_0 : Constant Convective heat transfer coefficients [W m^{-2} K^{-1}]
U_1 : Wind Dependent Convective heat transfer coefficient [W m^{-3} s^{-1} K^{-1}]
WS : Wind speed [m/s]

The efficiency of the module is calculated at reference conditions using the following:

$$\eta_{module} = \frac{P_{ref}}{H_{ref} * A_{module}} \quad \textbf{(4)}$$

Where,
P_{ref}: Rated power of the module at reference conditions (W)
H_{ref}: Irradiance at reference conditions (W·m^2)
A_{module}: Individual module area (m^2)

4.2.5 I-V Curve Parameters at Effective Conditions *void CalcIVCurveParameters(…)*

4.2.5.1 Diode Ideality Factor

The diode ideality factor has a temperature dependence which is fixed in the program at -0.001 [1/°C] for c-Si Modules (REF). The following equation is used to adjust the ideality factor at reference conditions to a calculated cell temperature, T_C:

$$\gamma = \gamma_{ref} - 0.001(T_c - T_{ref}) \tag{5}$$

4.2.5.2 Reverse Saturation Current

The reverse saturation current of the module is dependent upon cell temperature T_C and the relationship is defined using physical principles as below (REF):

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\frac{qE_g}{\gamma k}\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{6}$$

Where,
I_0 : Reverse Saturation Current
$I_{0,ref}$: Reverse Saturation Current at reference conditions
T_c : Calculated cell temperature [K] (see 4.2.4.5)
$T_{c,ref}$: Cell temperature at reference conditions (or at T_{ref}) [K]
q: Elementary Charge [C], Constant: $1.602 \text{ x } 10^{-19} C$
γ: Temperature adjusted diode ideality factor [1/K]
E_g: Band-gap of the cell material (CASSYS only simulation Si based solar modules, 1.12 eV)
k: Boltzmann Constant, 1.381 x 10^{-23} m^2 kg s^{-2} K^{-1}

4.2.5.3 Shunt Resistance

CASSYS uses the PVsyst irradiance-dependent shunt resistance model (7) which requires the definition of an exponential decay constant and a shunt resistance value at 0 irradiance, $R_{sh}(0)$. Review of prior work [5] shows that the best exponential parameter for any technology is 5.5 whereas, the $R_{sh}(0)$ is typically *4 x* $R_{sh,ref}$. CASSYS uses the values in the database for both of these parameters and uses the $R_{sh}(0) = 4 * R_{sh,ref}$ rule as a default if the value is not defined for a selected module.

$$R_{sh} = R_{sh,base} + \left[R_{sh}(0) - R_{sh,base}\right]\exp\left[-R_{sh,exp}\frac{H}{H_{ref}}\right] \tag{7}$$

Where,

R_{sh} : Irradiance adjusted shunt resistance of the module [Ω]
$R_{sh,base}$: Fitting parameter [Ω] defined as,

$$R_{sh,base} = R_{sh,ref} + R_{sh}(0) * \exp\left(-R_{sh,exp}\right) / \left(1 - \exp\left[-R_{sh,exp}\right]\right) \quad \textbf{(8)}$$

$R_{sh,exp}$: Exponential decay rate fixed to 5.5 in the program
H: Effective Plane of Array Irradiance [Wm^{-2}]
H_{ref}: Irradiance used at Reference Conditions [Wm^{-2}]

4.2.5.4 Photo-generated Current

Photo-generated current is affected by temperature which is calculated using the current temperature coefficient ($I_{sc,T-coeff}$) listed in the database for the module selected) and the irradiance through a proportionality relationship. The temperature coefficient is typically specified by module manufacturers in module datasheets. The equation to calculate effective photo-generated current at given temperature and irradiance takes the following form:

$$I_{\Phi} = \frac{H}{H_{ref}} \left[I_{\Phi,\mathrm{ref}} + I_{sc,T-coeff} (T_c - T_{ref}) \right] \quad \textbf{(9)}$$

Where,
I_{Φ}: Temperature and irradiance adjusted photo-current [A]
$I_{\Phi,\mathrm{ref}}$: Photo-current determined at reference conditions [see 4.2.4.14.2.4.1]
$I_{T-coeff}$: Current temperature coefficient [A/°C]
T_c: Calculated cell temperature [K] (see 4.2.4.5)
T_{ref}: Cell temperature at reference conditions (or at T_{ref}) [K]

4.2.5.5 Open-Circuit Voltage

Open-circuit voltage is affected by temperature and the relationship is best summarized by the voltage temperature coefficient ($V_{oc,T-coeff}$). To calculate the effective open-circuit voltage at given cell temperature one can use the following:

$$V_{oc} = V_{oc,ref} + V_{oc,T-coeff} * (T_c - T_{ref}) \quad \textbf{(10)}$$

Where,
V_{oc}: Temperature adjusted open-circuit voltage of the module [V]
$V_{oc,ref}$: Open-circuit voltage at reference conditions [V]
$V_{T-coeff}$: Open-circuit voltage temperature coefficient [V/°C]
T_c: Calculated cell temperature [K] (see 4.2.4.5)
T_{ref}: Cell temperature at reference conditions (or at T_{ref}) [K]
H: Effective Plane of Array Irradiance [Wm^{-2}]
H_{ref}: Irradiance used at Reference Conditions [Wm^{-2}]

4.2.6 Array to Inverter Wiring Resistance

The wiring resistance is specified by the user for the entire sub-array in terms of a percentage loss at maximum production by the modules in the sub-array ($R_{\%,STC}$). This loss percentage is translated to an equivalent wiring resistance R_w 'seen' by each module, using the following equation:

$$R_w = \frac{N_s}{N_p} R_{\%,STC} \left(\frac{P_{mpp}}{I_{mpp}{}^2} \right) \tag{11}$$

Where,
N_s: Number of modules in series in each string of the sub-array
N_p: Number of modules in parallel in the sub-array
P_{mpp}: Maximum power the module can produce [W]
I_{mpp}: Current of the module at the maximum power point [A]

This resistance is treated as an additional resistance in series with the series resistance. The effective equation for the SDM is then changed to:

$$I = I_{\Phi} - I_0 \left[e^{q\frac{[V+I(R_s+R_w)]}{N_{cells}\gamma k T_c}} - 1 \right] - \frac{V + I(R_s+R_w)}{R_{sh}} \tag{12}$$

4.2.7 Calculating Module Performance *void CalcAtMaximumPowerPoint()*

After the effective I-V curve parameters and the revised SDM equations are established, the module performance can be calculated based on the operating mode of the array (i.e. if the array is allowed to operate at its maximum power point (MPP) or at a fixed-voltage).

Due to the implicit nature of the revised SDM equation, the Newton-Raphson root-finding algorithm is used to determine the current produced by the module at any voltage V. For more information on how this algorithm is implemented, please see [6] and [7].

The maximum power of the module is then determined by the golden-ratio search algorithm [7].

4.2.8 Calculating Array Performance *void CalcModuleToArray(…)*

The calculations in 4.2.7 are done at the module level and must be translated to the array using the configuration of the modules. The current produced by the number of modules in parallel will add, whereas voltage for number of modules in series will add. The effective current and voltage are determined after applying the following losses to the array performance. The losses currently accepted by CASSYS (v 0.9) are discussed briefly in the next few sub-sections.

4.2.8.1 Module Quality Loss:

The user provides a percentage loss ($L_{\%,modquality}$) at standard conditions reflecting losses in module quality due to LID and module aging, etc. The loss is calculated using the following:

$$L_{modquality} = I_{array} \cdot L_{\%,modquality} \cdot V_{array} \tag{13}$$

This percentage is then applied to the current produced by the array and a new current value is determined:

$$I_{array,1} = I_{array}\left(1 - L_{\%,modquality}\right) \quad (14)$$

4.2.8.2 Mismatch Loss

The user provides a percentage loss occurring due to the mismatch of module current-voltage characteristics results. The losses resulting from this mismatch would be different if the array is operating at its maximum power point (MPP) or if it forced by the inverter to operate at a fixed voltage (FV). Hence, the user can provide a percentage loss at each condition. Typically the fixed voltage operating mode incurs a higher performance penalty. The percentage loss is applied to the current produced by the array based on the operating mode.

$$L_{mismatch} = I_{array} \cdot L_{\%\,mismatch,FV/MPP} \cdot V_{array} \quad (15)$$

This percentage is then applied to the current produced by the array and a new current value is determined:

$$I_{array,2} = I_{array,1}\left(1 - L_{\%\,mismatch,FV/MPP}\right) \quad (16)$$

4.2.8.3 Ohmic Losses

Given the effective wiring resistance (R_w) for the entire sub-array (see 4.2.6), the ohmic loss is calculated using ohms law:

$$L_{ohmic} = I_{array,2}^2 \cdot R_w \quad (17)$$

4.2.8.4 Soiling Losses

As discussed earlier (4.2.8.4), the soiling loss percentage specified by the user is directly applied to the incident irradiance. To estimate the power lost to soiling, the program calculates the losses using the following:

$$L_{soiling} = I_{array} \cdot \frac{L_{\%,soiling}}{(1 - L_{\%,soiling})} \cdot V_{array} \quad (18)$$

4.2.8.5 Power Produced by the Array

Since all other losses are accounted for by reducing the effective current produced by the array, the ohmic loss is applied in the end. The total power produced by the array after all is then given by:

$$P_{array} = V_{array} \cdot I_{array} - L_{ohmic} \quad (19)$$

4.3 Shading *Shading.cs*

This class calculates the shading factors on the beam, diffuse and ground-reflected components of incident irradiance based on the sun position throughout the day resulting from a near shading model. Shading models are available for panels arranged in an unlimited rows or a fixed tilt configuration. If the unlimited row model is to be used, the model can be further customized to use a linear shading model or a cell based (step-wise) shading model.

4.3.1 Inputs

Sun Zenith	*Zenith angle of the sun (rad)*
Sun Azimuth	*Azimuth angle of the sun (rad)*
POA Beam Irradiance	*Beam component of POA irradiance ($W \cdot m^{-2}$)*
POA Diffuse Irradiance	*Diffuse component of POA irradiance ($W \cdot m^{-2}$)*
POA Ground-Reflected Irradiance	*Ground reflected component of POA Irradiance ($W \cdot m^{-2}$)*

4.3.2 Outputs

Beam Shading Factor (SF)	*Shading factor applied to POA Beam Irradiance*
Diffuse SF	*Shading factor applied to POA Diffuse Irradiance*
Ground-Reflected SF	*Shading factor applied to POA Ground-Reflected Irradiance*
Profile Angle	*Profile angle of the sun [see (20)]*
Shaded Global POA Irradiance	*Sum of all components after respective shading factors are applied ($W \cdot m^{-2}$)*
Shaded Beam POA Irradiance	*POA Beam Irradiance with SF applied ($W \cdot m^{-2}$)*
Shaded Diffuse POA Irradiance	*POA Diffuse Irradiance with SF applied ($W \cdot m^{-2}$)*
Shaded Ground-Reflected POA Irradiance	*POA Ground-Reflected Irradiance with SF applied ($W \cdot m^{-2}$)*

4.3.3 Parameters

Fixed-Tilt Configuration:

Plane of Array Tilt	*Tilt of the modules installed relative to the ground (rad)*
Plane of Array Azimuth	*Azimuth angle of the modules relative to True South (rad)*

For the Unlimited Rows Configuration, the following are required in addition to the above (see Figure 5):

SLA	*Shading Limit Angle*
Width of Active Area	*See Figure 5 (m)*
Pitch	*Distance between consecutive rows of modules (m)*
Number of Rows	*Number of rows in the far, Unlimited Rows Configuration*

The above parameters allow for the calculation of a linear shading model (with respect to Profile Angle), for the non-linear shading model, the following additional parameters are required (see Figure 5):

Number of Modules	*Number of modules in width of active area*
Cell Size	*Size of the cell in the transverse direction (cm)*

4.3.4 Shading Model for Unlimited Rows Configuration

The unlimited row configuration is an array configuration in which panels are placed on racking with a fixed tilt with rows of such racks placed behind one another. CASSYS considers the length of such rows to be long enough to not consider any edge effects in its shading model. This assumption reduces the calculation of the shading factor at different times of the day to a simple geometrical construct. The user can specify the following parameters regarding the row orientation summarized in the image below:

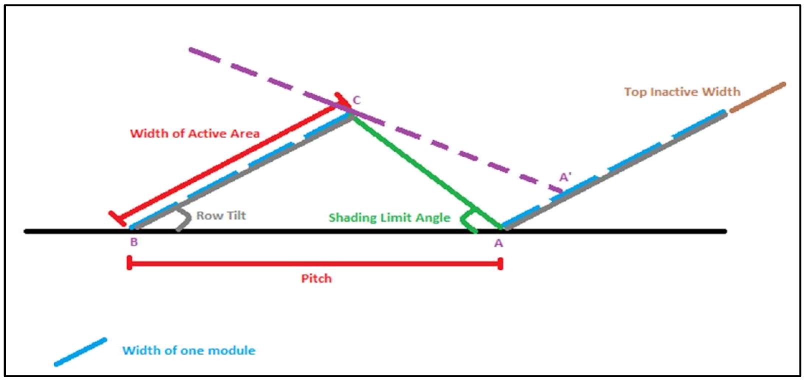

Figure 5: Unlimited Rows Orientation and Shading Analysis

The shading limit angle (SLA) is the angle formed by the top inactive width (if defined as shown in row 2) to the bottom of the active area for the following row. It is determined using the cosine law (two sides and an angle of the triangle ABC are known). This calculation is done in the interface and provided to the user. The second useful angle is the profile angle of the sun at a given time. The profile angle (*PA*) is defined as the projection of the solar altitude angle (complement of zenith angle) on a vertical plane perpendicular to the array [3]. For a given Sun Zenith (S_Z) and Azimuth (S_A) and for a Collector Azimuth (C_A), the PA is calculated with equation (20).

$$PA = \arctan\left[\frac{\tan\left(\frac{\pi}{2} - S_Z\right)}{\cos(S_A - C_A)}\right] \quad \textbf{(20)}$$

4.3.4.1 Linear Shading Factor on the POA Beam Component

For shading to occur, the profile angle of the sun must be lower than the shading limit angle. If this is true, the length of AA' is the portion of a row shaded by the preceding row. To determine the length of the shaded portion, the following equations (21)-(36) are used:

$$AC = \frac{\sin(Row\ Tilt)}{\sin(SLA)} Collector\ Width \quad \textbf{(21)}$$

$$\angle CAA' = \pi - Row\ Tilt - SLA \quad \textbf{(22)}$$

$$\angle CA'A = \pi - CAA' - (SLA - PA) \quad \textbf{(23)}$$

$$AA' = \frac{AC\ \cdot\ \sin(SLA - PA)}{\sin(CA'A)} \quad \textbf{(24)}$$

The shaded fraction for the beam component is given by the ratio of the collector width and the AA' calculated from equation (36).

4.3.4.2 Cell-based Shading Model on the POA Beam Component

In the cell-based shading model, the entire section (modules placed alongside in the length of the row) is considered inactive as soon as the first cell of that module is completely shaded. Once the length of the shaded section is calculated from (24), the model determines the number of cells under this section (25).

$$N_{cells\ shaded} = \frac{AA'}{Cell\ Size} \quad (25)$$

When the last cell of section S is shaded by the preceding row, the shading fraction is the ratio of the section number and the total number of sections (or modules) in the active area width.

$$SF_S = \frac{S}{N_{modules,Active\ Area}} \quad (26)$$

The shading fraction maximizes for a given section at SF_s once a module is completely shaded, and follows a linear pattern until the first cell in each module section is completely shaded.

4.3.4.3 Shading factor on the POA Diffuse Component

The shaded fraction for the diffuse component is calculated using the view factor of the sky for a tilted surface obstructed by the row in front of it. For more information regarding view factor integrals, please see [8].

$$Diffuse\ Shading\ Fraction = \frac{1 + \cos(SLA)}{2} \quad (27)$$

4.3.4.4 Shading factor on the POA Ground-Reflected Component

Due to the arrangement of the rows, only the rows other than the first row will experience shading from preceding rows. CASSYS adjusts for this by scaling the shading factors based on a row block factor. The row block factor is given by (28). This is applied to the diffuse and beam shading factor as above in the linear shading case. This adjustment is not applied to the beam shading factor calculated using the cell based shading model.

$$Row\ Block\ Factor = \frac{Number\ of\ Rows - 1}{Number\ of\ Rows} \quad (28)$$

Using the above, the shading factor for the ground-reflected component is given by (28)(36).

$$Ground\ Reflected\ Shading\ Factor = 1 - Row\ Block\ Factor \quad (29)$$

From the definition of the diffuse and ground-reflected shading factor, it is clear that these remain constant over the year, and hence are calculated only once by the program.

4.4 Simulation — Simulation.cs

4.5 Splitter — Splitter.cs

This class calculates beam and diffuse irradiance, given global horizontal irradiance (or its components).

4.5.1 Inputs

Sun Zenith	*Zenith angle of the sun [radians]*
Global Horizontal Irradiance	*Measured/Calculated ($W \cdot m^{-2}$)*
Diffuse Horizontal Irradiance	*Measured ($W \cdot m^{-2}$)*
Direct Normal Irradiance	*Measured ($W \cdot m^{-2}$)*

Direct Horizontal Irradiance	*Measured ($W \cdot m^{-2}$)*
Normal Extraterrestrial Irradiance	*Measured ($W \cdot m^{-2}$)*

4.5.2 *Outputs*

Global Horizontal Irradiance	*($W \cdot m^{-2}$)*
Diffuse Horizontal Irradiance	*($W \cdot m^{-2}$)*
Direct Normal Irradiance	*($W \cdot m^{-2}$)*
Direct Horizontal Irradiance	*($W \cdot m^{-2}$)*

4.5.3 *Parameters*

Under Development

4.5.4 *Equations and Model Description*

Under Development

4.6 Sun — Sun.cs

The Sun class is an object used to compute solar zenith and azimuth angles.

4.6.1 *Inputs*

Day of the year	*1 to 365 (Leap Year: 29 Feb and March 1 is treated as the same day)*
Hour of the Day	*24-Hour Decimal Format (11.75 is 11:45)*

4.6.2 *Outputs*

Zenith	*Zenith angle of sun [rad]*
Azimuth	*Azimuth of sun [rad, >0 facing E]*
AirMass	*Air mass [#]*
NExtra	*Extraterrestrial normal Irradiance [W/m2]*
AppSunsetHour	*Sunset hour (uses Tilt to calculate the Sunset Hour)*
AppSunriseHour	*Sunrise hour (uses Tilt to calculate the Sunset Hour)*
TrueSunSetHour	*The true Sunset hour*
TrueSunRiseHour	*The true sunrise hour*

4.6.3 *Parameters and Cached Variables*

Site Lat	*Latitude of the Site (°N is Positive, °S is Negative)*
Site Long	*Longitude of the Site (°E is Positive)*
Site Meridian	*Reference Meridian for Local Standard Time at Site (°E is Positive), required when climate file is in local time*
Slope of Collector	*Slope of the plane of array (radian)*
Current Day	*Cached, Current day of year (to speed up daily calculations)*
Current Declination	*Cached, Declination for Current Day*
Current Extra-terrestrial Radiation	*Cached, Extra-terrestrial radiation for current day*

4.6.4 *Equations and Model Descriptions*

Under development

4.7 Transformer — Transformer.cs

CASSYS models two types of losses for the grid-connected transformer, the core or iron losses and the ohmic losses.

4.7.1 *Inputs*

Input Power	*Power going from inverters to the low-side of the transformer (W)*
Global Loss	*Total loss of the transformer at Rated Transformer Power (W), calculated (see 4.7.4)*
Core or Iron-Loss	*Loss under no-load conditions (see 4.7.3)*
Nightly Disconnected	*Boolean, if the transformer is designed to disconnect at night*

4.7.2 *Outputs*

Power Produced	*Power delivered to the grid by the transformer (W)*
Ohmic Losses	*Losses due to internal resistance of the windings (see 4.7.3.2)*
Total Losses	*Losses due to the core and ohmic losses*

4.7.3 *Parameters*

4.7.3.1 Core Losses

Some of the input power on the primary side of the transformer is used to compensate for the core losses (composed of hysteresis and eddy currents) occurring within the transformer. The user can specify the power lost to core losses for a grid-connected transformer (or a combination of inverter transformers and grid-connected transformers) directly. Since this loss occurs under no-load conditions, this is modelled as a constant loss by CASSYS as long as the transformer is not disconnected.

4.7.3.2 Ohmic Losses

Input power is also lost to the internal resistance of the primary and secondary windings. This loss is also called the copper loss of the transformer. This is typically dissipated as heat and can be modelled with an effective resistance. Users can specify the percentage loss expected when the array is subject to STC conditions ($L_{\%,OhmicT,STC}$) which is interpreted to an STC Loss of the transformer using (30).

$$L_{OhmicT,STC} = L_{\%,OhmicT,STC} \cdot \eta_{Inv} \cdot PDC_{STC} \quad \textbf{(30)}$$

Where,

η_{Inv} : Efficiency of the Inverters (assumed to be 95%)

PDC_{STC}: STC rated capacity of the farm

4.7.3.3 Nightly Disconnect

Core losses of the transformer could add up to a substantial amount over a year (~1% of annual production). Hence, some sites are designed to disconnect the transformer at night. CASSYS models this by disconnecting the transformer when the *sun sets for the day under simulation* when the user selects the night disconnection option.

4.7.4 Modelling Transformer Loss

Transformer losses are the sum of the iron and resistive/inductive losses. The core losses are constant and the ohmic losses are quadratic. The following definition of the global loss of the transformer at its nominal rated power can be used:

$$L_{Global,Nom} = L_{IronLoss,Nom} + L_{OhmicLoss,Nom} \quad \textbf{(31)}$$

From the above, the ohmic losses at nominal transformer power are unknown. The ohmic losses at nominal conditions are calculated by scaling down the losses in (30) to the transformer rated power using the quadratic relationship:

$$L_{OhmicLoss,Nom} = L_{OhmicLoss,STC} \cdot \left(\frac{P_{Nom,T}}{\eta_{Inv} \cdot PDC_{STC}}\right)^2 \quad \textbf{(32)}$$

This provides the Global losses at nominal power of the transformer. This relationship is then used to determine the power loss from an input power, P_{Input} using

$$L_{OhmicLoss,P_{Input}} = \left(L_{Global,Nom} - L_{IronLoss,Nom}\right) \cdot \left(\frac{P_{Input}}{P_{Nom,T}}\right)^2 \quad \textbf{(33)}$$

The loss at any input power is then calculated using the relationship in (31) as the iron losses remain constant.

5 Classes with Mathematical Constructs

The following classes are static classes and contain mathematical constructs that enable the calculation of several different values that are used in the main classes above.

5.1 Daily Astronomical Calculations *Astro.cs*

The Astro class contains a set of methods to calculate sun position, air mass, day length, etc. This class is a static class and does not require any parameters from the user.

5.1.1 List of Methods

Under development

5.1.2 Physical Model and Methods Description

Under development

5.2 Interpolate *Interpolate.cs*

This class contains 2 methods that enable Linear and Quadratic Interpolation for arrays of varied lengths. This class is used exclusively to model Inverter Efficiency (see: 4.1.4).

5.2.1 *Equations and Methods Description*

5.2.1.1 Linear Interpolation *public static double Linear (…)*

For a given interpolant x_v, CASSYS uses linear interpolation using two arrays x and y each with n entries to determine y_v. First, the program determines the interval number k, such that $x_k < x_v < x_{k+1}$. The following formulae can then be used.

$$y_v = y_k \frac{(x_{k+1} - x_v)}{(x_{k+1} - x_k)} + y_{k+1} \frac{(x_v - x_k)}{(x_{k+1} - x_0)} \tag{34}$$

If x_v lies outside of these bounds, an extrapolation formula is used, ensuring the continuity and smoothness of the overall curve. The following formula is used with *k = 0* when extrapolating to the left and *k = n-1* when extrapolating to the right:

$$y_v = y_i + (x_v - x_{k+1}) \cdot \frac{(y_{k+1} - y_k)}{(x_{k+1} - x_k)} \tag{35}$$

5.2.1.2 Quadratic Interpolation *public static double Quadratic (…)*

CASSYS only allows the use of quadratic interpolation [7] for three input values (see Inverter.cs). This allows for the use of the Lagrange interpolating polynomial of degree 2 to obtain $P(x)$ as below:

$$P(x) = \frac{(x - x_2)(x - x_2)}{(x_1 - x_2)(x_1 - x_3)} y_0 + \frac{(x - x_1)(x - x_3)}{(x_2 - x_1)(x_2 - x_3)} y_1 + \frac{(x - x_1)(x - x_2)}{(x_3 - x_1)(x_3 - x_2)} y_2 \tag{36}$$

5.3 Tilt *Tilt.cs*

The Tilt class contains a set of methods to calculate solar radiation on tilted surfaces, as well as the object to encapsulate them.

5.3.1 *List of Methods*

Under development

5.3.2 *Physical Models and Descriptions*

Under development

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