Smart Inverter Modelling using Dynamic Phasors

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1. Introduction

Dynamic models of Distributed energy resources (DER’s) are required to analyze the performance of control systems, and evaluate stability and may be either linear or non-linear. In the Dynamic phasor approach, voltage/current waveforms are decomposed into their components over a time interval using Fourier series, and the time-evolution of the Fourier series coefficients are modeled using ODE’s. Dynamic phasors allow the creation of models with a large number of converters without adversely increasing the required computation time. This project worked on developing a dynamic phasor model for a PV –DER with smart inverter features. An overview of the simulated components in the model is given in Fig. 1. Detailed specifications for each of these components are provided from page 5 onwards.



Fig. 1.Grid-connected solar PV-DER model

1. Model Parameters and Nominal Values

Table 1. Base values for per unit calculations

|  |  |  |
| --- | --- | --- |
| **Base parameter** | **Formula** | **Value** |
|  | N.A | 50 kVA |
|  | N.A | 500 V |
|  | N.A | 2π60 |
|  |  | 5 ohm |
|  |  | 0.013 |
|  |  | 0.0005 |

Table 2. Nominal values for model variables

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Base parameter** | **Value** |
| Solar insolation power rating |  | 100 W/cm2 |
| DC link voltage |  | 500 V |
| Grid voltage source – voltage |  | 25000 V |
| Grid voltage source – frequency |  | 60 Hz |

Table 3. Model parameters

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Symbol** | **Default value** |
| DC link capacitance |  | 30.0e-6 F |
| Inverter Filter inductance |  | 2.5e-6 H |
| Inverter Filter resistance |  | 0.0019 Ohm |
| Transformer equivalent circuit |  | 0.0018 + 0.056j |
| Transmission line equivalent circuit |  | 1.61+5.54j |
| Transformer turns ratio |  | 100 |

# PV Module – power output

# Model description

Type: Steady state

Function: Calculate power output from PV panel for given insolation and temperature.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 11 | N.A. | Parallel connected solar cells |
|  | 660 | N.A. | Series connected solar cells |
|  | 8.03 | A | Cell short-circuit current at reference temperature and radiation |
|  | 0.0017 |  |  |
|  | 300 | K | Cell reference temperature |
|  | 1.20E-07 | A | Cell reverse saturation current |
|  | 1.60E-19 | C | Charge of an electron |
|  | 1.38E-23 | m2kgs-2K-1 | Boltzmann's constant |
|  | 1.92 | N.A. | p-n junction ideality factor |
|  | 500 | V | DC Base voltage |

# Model inputs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Default value | Unit | Description | Source |
|  | 100.0 | mW/cm2 | Incident solar insolation | User specified |
|  | 300.0 | K | PV panel temperature | User specified |

# Model equations

 (1)

 (2)

 (3)

# Model block diagram



# PV Module - MPP algorithm

# Model description

Type: Iterative

Function: Calculate maximum power point voltage for PV panel.

# Model constants (some are shared with PV Module – power output)

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 500 | V | Voltage at maximum power point (initial) |

# Model inputs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Default value | Unit | Description | Source |
|  | 100.0 | mW/cm2 | Incident solar insolation | User specified |
|  | 300.0 | K | PV panel temperature | User specified |

# Model equations

 (1)

# Model block diagram



# DC Link Capacitor - voltage

# Model description

Type: Dynamic

Function: Calculates voltage across DC link capacitor

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.056 | C | DC link capacitor capacitance |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 1.0 | V (p.u.) | Voltage across DC link |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 1.0 | W (p.u.) | PV Module – power output |
|  | 1.0 | W (p.u.) | Inverter Terminal - power output |

# Model equations

 (1)

# Model block diagram



# VSC Inverter - DC link voltage controller

# Model description

Type: Dynamic

Function: Calculates real current reference for current controllers.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | -1.0 | N.A. | Proportional constant |
|  | -100.0 | N.A. | Integral constant |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 0.0 | N.A. | Proportional constant |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source |
|  | 1.0 | V (p.u.) | User specified voltage reference |
|  | 1.0 | V (p.u.) | DC Link Capacitor - voltage |

# Model equations

 (1)

 (2)

 (3)

# Model block diagram



# VSC Inverter - reactive power controller

# Model description

Type: Dynamic

Function: Calculates imaginary current reference value for current controllers.

# Model constants

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Serial Number | Symbol | Default value | Unit | Description |
| 1 |  | 0.01 | N.A. | Proportional constant |
| 2 |  | 0.5 | N.A. | Integral constant |

# Model states

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Serial Number | Symbol | Initial value | Unit | Description |
| 1 |  | 0.0 | N.A. | Integral state |

# Model inputs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Serial Number | Symbol | Initial value | Unit | Source |
| 1 |  | 0.0 | VAR (p.u.) | User specified/Volt-VAR control |
| 2 |  | 0.0 | VAR (p.u.) | PCC LV side – power output |

# Model equations

 (1)

, (2)

 (4)

# Model block diagram



# VSC Inverter - current controller

# Model description

Type: Dynamic

Function: Calculates average duty cycle for inverter switching.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.01 | N.A. | Proportional constant |
|  | 0.5 | N.A. | Integral constant |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 0.0 | N.A. | Integral state |
|  | 0.0 | N.A. | Integral state |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | A (p.u.) | VSC Inverter - DC link voltage controller |
|  | 0.0 | A (p.u.) | VSC Inverter - reactive power controller |
|  | 0.0 | A (p.u.) | VSC Inverter - current |

# Model equations

 (1)

 (2)

 (3)

# Model block diagram



# Grid Voltage Source - voltage

# Model description

Type: Dynamic

Function: Dynamics of grid voltage source.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.001 | s | Time constant for change in grid voltage |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 0.0 | V (p.u.) | Grid voltage – real |
|  | 0.0 | V (p.u.) | Grid voltage – imaginary |

# Model inputs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Default value | Unit | Description | Source |
|  | 50.0 | V (p.u.) | Grid voltage reference | User specified |
|  | 376.0 | rad/s | Grid frequency reference | User specified |

# Model equations

 (1)

# Model block diagram



# Inverter Terminal - voltage

# Model description

Type: Steady state

Function: Calculates voltage at inverter terminals (before filter).

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | N.A. | VSC Inverter - current controller |
|  | 0.0 | N.A. | DC Link Capacitor - voltage |

# Model equations

 (1)

# Model block diagram



# PCC LV side - voltage

# Model description

Type: Steady state

Function: Calculates voltage at point of common coupling between inverter and grid.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.00038+0.0112j | Ohm (p.u.) | Transformer equivalent circuit (referred to primary) |
|  | 0.322+1.108j | Ohm (p.u.) | Transmission line impedance (20 km length) |
|  | 100 | N.A. | Transformer ratio |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | A (p.u.) | VSC Inverter - current |
|  | 0.0 | N.A. | Grid voltage source - voltage |

# Model equations

 (1)

# Model block diagram



# VSC Inverter - current

# Model description

Type: Dynamic

Functions: Calculates inverter current.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.01 | H | Filter inductance |
|  | 0.5 | Ohm | Filter resistance |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 0.0 | A (p.u.) | Inverter current – real |
|  | 0.0 | A (p.u.) | Inverter current – imaginary |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | V (p.u.) | PCC LV side - voltage |
|  | 0.0 | V (p.u.) | Inverter terminal - voltage |
|  | 0.0 | N.A. | VSC Inverter - current controller |
|  | 376.0 | rad/s | VSC Inverter - PLL |

# Model equations

 (1)

# Model block diagram



# Inverter Terminal - power output

# Model description

Type: Steady state

Function: Calculates active and reactive power output at inverter terminals.

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | V (p.u.) | Inverter terminal - voltage |
|  | 0.0 | A (p.u.) | VSC Inverter - current |

# Model equations

 (1)

# Model block diagram



# PCC LV side – power output

# Model description

Type: Steady state

Function: Calculates active and reactive power output at inverter terminals.

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | V (p.u.) | PCC LV side - voltage |
|  | 0.0 | A (p.u.) | VSC Inverter - current |

# Model equations

 (1)

# Model block diagram



# Inverter Features - Volt-VAR Control

# Model description

Type: Steady state

Function: Calculate reactive power set-point.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.5 | VAR (p.u.) | Inverter reactive power supply/absorb limit |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source |
|  | 1.0 | V (p.u.) | PCC LV side - voltage |

# Model equations

 (1)

# Model block diagram



# Inverter Features - LVRT Logic

# Model description

Type: Steady state

Function: Apply Low voltage ride through (LVRT) logic to generate DER trip signal.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | N.A. | V | Low voltage levels |
|  | N.A | s | Time limits at various voltage levels |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source |
|  | 1.0 | V (p.u.) | PCC LV side - voltage |

# Logic flowchart



# Inverter Features - LFRT Logic

# Model description

Type: Steady state

Function: Apply Low-frequency ride through (LFRT) logic to generate DER trip signal.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | N.A. | V | Low-frequency levels |
|  | N.A | s | Time limits at various frequency levels |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source |
|  | 376.0 | rad/s | VSC Inverter - PLL |

# Logic flowchart



# VSC Inverter - PLL

# Model description

Type: Dynamic

Function: Calculates inverter frequency based on a synchronous reference frame – phase locked loop.

# Model constants

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Description |
|  | 0.01 | N.A. | Proportional constant |
|  | 0.5 | N.A. | Integral constant |
|  | 376.0 | rad/s | Nominal frequency |

# Model states

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Initial value | Unit | Description |
|  | 0.0 | N.A. | PLL integral state |
|  | 2π | rad | PLL angle integral state |

# Model inputs

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Default value | Unit | Source model |
|  | 0.0 | V (p.u.) | PCC LV side – voltage |
|  |  | rad/s | User defined |

# Model equations

 (1)

 (2)

 (3)

 (4)

# Model block diagram

