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GridLAB-D Technical Support Document: Power Flow – Sweeping Method Version 1.0

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CE Gerkensmeyer

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Contents

1.0 Introduction

This documentation explains the technical aspects of the Power Flow Module – Sweeping Method Version 1.0, implemented for GridLAB-D. The power flow module provides electrical distribution system modeling for power flow solutions. A power flow calculation is performed to determine what the node voltages and line currents are at each point of the system, given the system model, electrical loads connected at each node, and voltage at the substation.

The power flow problem is solved using a three-phase, forward-back sweep method. The specific methodology and equations are described in Kersting (2007). The basic equations are in the following forms:

backward sweep

$$[I_{abc}]_n = [c]\cdot[V_{abc}]_m + [d]\cdot[I_{abc}]_m, \tag{1.1}$$

forward sweep

$$[V_{abc}]_m = [A]\cdot[V_{abc}]_n - [B]\cdot[I_{abc}]_m \tag{1.2}$$

where the *c, d, A,* and *B* matrices represent individual characteristics of each link section as described in Kersting (2007).

2.0 Component Modeling

The method used for modeling components in the power flow module is consistent with Kersting (2007). The following sections are included to address any differences between our method and those described in Kersting (2007).

2.1 Overhead and Underground Lines

Overhead and underground (concentric neutral and tape-shield) lines are both supported. Single-phase and three-phase lines with a neutral conductor are supported. Systems with more than 3 phases, i.e. n-phase configurations, are not currently supported. Equations used are consistent with Kersting (2007).

2.2 Secondary Lines

Single-phase triplex secondary cable is supported. Equations used are consistent with Kersting (2007).

2.3 Transformers

For three-phase Delta-connected secondary transformers, the impedance within the Delta windings must be calculated. With standard transformer per unit calculations, the secondary line impedance is calculated. Equivalent impedance within the Delta is calculated by multiplying the calculated transformer secondary impedance by 3. The equations for Delta secondary in the following subsections use the impedance within the Delta.

For single-phase transformers connected in a three-phase Delta configuration, the impedance of each individual transformer is equivalent to the impedance within the Delta. Therefore, calculation of the secondary impedance is straightforward.

These equations are assuming that the transformers modeled are consistent with C57.12.00 (2006):

> *"The angular displacement between high-voltage and low-voltage phase voltages of three-phase transformers with Y- Δ or Δ -Y connections shall be 30º, with the low voltage lagging the high voltage…"*

Equations for Wye-Wye or Delta-Delta are the same for step-up or step-down transformers. Equations for step-up and step-down cases are different for the Wye-Delta and Delta-Wye connections because of the “American Standard Thirty Degree” connection, as described in Kersting (2007) and C57.12.00 (2006). Supported transformers and are discussed in the following subsections.

2.3.1 Delta-Grounded Wye (Step-down)

Equations for the Delta-Grounded Wye step-down transformer are consistent with Kersting (2007).

2.3.2 Delta-Grounded Wye (Step-up)

The equations for the step-up and step-down transformer are not identical because of the use of the “American Standard Thirty Degree” connection, as described in Kersting (2007) and C57.12.00 (2006). In order to obtain the equations for the step-up transformer from the step-down transformer equations the *c* and *d* matrices must be multiplied by:

$$S = \begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \tag{2.1}$$

Matrix A must be multiplied by:

$$S^{-1} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix} \tag{2.2}$$

2.3.3 Ungrounded Wye-Delta (Step-down)

Equations for the Ungrounded Wye-Delta step-down transformer are consistent with Kersting (2007).

2.3.4 Ungrounded Wye-Delta (Step-up)

The equations for the step-up and step-down transformer are not identical because of the use of the "American Standard Thirty Degree" connection, as described in Kersting (2007) and C57.12.00 (2006). In order to obtain the equations for the step-up transformer from the step-down transformer equations the *c* and *d* matrices must be multiplied by:

$$S = \begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \tag{2.3}$$

Matrix A must be multiplied by:

$$S^{-1} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix} \tag{2.4}$$

2.3.5 Grounded Wye-Grounded Wye (Step-up and Step-down)

Equations for the Grounded Wye-Grounded Wye step-up and step-down transformers are consistent with Kersting (2007).

2.3.6 Delta-Delta (Step-up and Step-down)

Equations for the Delta-Delta step-up and step-down transformers are consistent with Kersting (2007).

2.3.7 Open Wye-Open Delta (Step-down)

Equations for the Open Wye-Open Delta step-down transformers are consistent with Kersting (2007).

2.3.8 Single-Phase (Step-down)

Not yet implemented.

2.3.9 Single-Phase Center-Tapped (Step-down)

Single-phase center-tapped transformers mark the transition point between the primary and secondary distribution system. These are the transformers that step the voltage down from the primary distribution system voltage (for example, 12.47 kV) to the residential voltage (120 V and 240 V).

Transformers are modeled using an interlaced design. The representative equations are created using the method described in Kersting (2007), with the exception that 3 x 3 matrices are in used in lieu of 2 x 2 matrices. The specific formats are shown below in sections 2.3.9.1, 2.3.9.2, and 2.3.9.3.

2.3.9.1 A-Phase Connected Primary

$$[a] = \begin{bmatrix} n_t & 0 & 0 \\ n_t & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.5}$$

$$[b] = \begin{bmatrix} n_t \cdot Z_1 + \frac{1}{n_t} \cdot Z_0 & -\frac{1}{n_t} \cdot Z_0 & 0 \\ \frac{1}{n_t} \cdot Z_0 & -\left(n_t \cdot Z_2 + \frac{1}{n_t} \cdot Z_0 \right) & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.6}$$

$$[c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.7}$$

$$[d] = \frac{1}{n_t} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.8}$$

$$[A] = \begin{bmatrix} \frac{1}{n_t} & 0 & 0 \\ \frac{1}{n_t} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.9}$$

$$[B] = \begin{bmatrix} Z_1 + \frac{1}{n_t^2} \cdot Z_0 & -\frac{1}{n_t^2} \cdot Z_0 & 0 \\ \frac{1}{n_t^2} \cdot Z_0 & -\left(Z_2 + \frac{1}{n_t^2} \cdot Z_0 \right) & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.10}$$

2.3.9.2 B-Phase Connected Primary

$$[a] = \begin{bmatrix} 0 & n_t & 0 \\ 0 & n_t & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.11}$$

$$[b] = \begin{bmatrix} n_t \cdot Z_1 + \frac{1}{n_t} \cdot Z_0 & -\frac{1}{n_t} \cdot Z_0 & 0 \\ \frac{1}{n_t} \cdot Z_0 & -\left(n_t \cdot Z_2 + \frac{1}{n_t} \cdot Z_0 \right) & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.12}$$

$$[c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.13}$$

$$[d] = \frac{1}{n_t} \cdot \begin{bmatrix} 0 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.14}$$

$$[A] = \begin{bmatrix} 0 & \frac{1}{n_t} & 0 \\ 0 & \frac{1}{n_t} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.15}$$

$$[B] = \begin{bmatrix} Z_1 + \frac{1}{n_t^{\;2}} \cdot Z_0 & -\frac{1}{n_t^{\;2}} \cdot Z_0 & 0 \\ \frac{1}{n_t^{\;2}} \cdot Z_0 & -\left(Z_2 + \frac{1}{n_t^{\;2}} \cdot Z_0 \right) & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.16}$$

2.3.9.3 C-Phase Connected Primary

$$[a]=\begin{bmatrix}0 & 0 & n_t\\ 0 & 0 & n_t\\ 0 & 0 & 0\end{bmatrix} \tag{2.17}$$

$$[b]=\begin{bmatrix}n_t\cdot Z_1+\frac{1}{n_t}\cdot Z_0 & -\frac{1}{n_t}\cdot Z_0 & 0\\ \frac{1}{n_t}\cdot Z_0 & -\left(n_t\cdot Z_2+\frac{1}{n_t}\cdot Z_0\right) & 0\\ 0 & 0 & 0\end{bmatrix} \tag{2.18}$$

$$[c]=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \tag{2.19}$$

$$[d]=\frac{1}{n_t}\cdot\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 1 & -1 & 0\end{bmatrix} \tag{2.20}$$

$$[A]=\begin{bmatrix}0 & 0 & \frac{1}{n_t}\\ 0 & 0 & \frac{1}{n_t}\\ 0 & 0 & 0\end{bmatrix} \tag{2.21}$$

$$[B]=\begin{bmatrix}Z_1+\frac{1}{n_t^{\,2}}\cdot Z_0 & -\frac{1}{n_t^{\,2}}\cdot Z_0 & 0\\ \frac{1}{n_t^{\,2}}\cdot Z_0 & -\left(Z_2+\frac{1}{n_t^{\,2}}\cdot Z_0\right) & 0\\ 0 & 0 & 0\end{bmatrix} \tag{2.22}$$

Voltage and current values used for the secondary system sweeps are shown below.

2.3.9.4 Backward Sweep

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = [c] \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_n \end{bmatrix} + [d] \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_n \end{bmatrix} \tag{2.23}$$

2.3.9.5 Forward Sweep

$$\begin{bmatrix} V_1 \\ V_2 \\ V_n \end{bmatrix} = [A] \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} - [B] \cdot \begin{bmatrix} I_1 \\ I_2 \\ I_n \end{bmatrix} \tag{2.24}$$

where:

I_A, I_B, I_C = Primary current

I_1, I_2, I_n = Secondary current

V_A, V_B, V_C = Primary voltage

V_1, V_2, V_n = Secondary voltage

2.4 Regulators

Single-Phase Wye connected, Single-Phase Delta connected, and Single-Phase Open Delta regulators all are supported. Equations used are consistent with Kersting (2007).

2.5 Switch

System line switches are modeled as shown below.

If in service, Z=.0001
If out of service, Z=infinite

$$[a] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad [b] = \lfloor Z_{abc} \rfloor \quad [c] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad [d] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.25}$$

$$[A] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad [B] = \lfloor Z_{abc} \rfloor \tag{2.26}$$

2.6 Fuse

System line fuses have been modified as a simple over-current device. The equations are shown below.

If current < I_{min}, Z=.0001
If current > I_{min}, Z=infinite

$$[a]=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\ [b]=\lfloor Z_{abc}\rfloor\ [c]=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\ [d]=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} \tag{2.27}$$

$$[A]=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\ [B]=\lfloor Z_{abc}\rfloor \tag{2.28}$$

3.0 References

Kersting WH. 2007. *Distribution System Modeling and Analysis.* Second Edition. CRC Press, Boca Raton, Florida.

C57.12.00-2006. *IEEE Standard for Standard General Requirements for Liquid Immersed Distribution, Power, and Regulating Transformers*. Available online at: www.ieee.org