EPIGRIDS: Electric Power Infrastructure and Grid Representations in Interoperable Data Sets

Professor Chris DeMarco
Department of Electrical & Computer Engineering
University of Wisconsin-Madison

IEEE PES Power & Energy Society®

IEEE

Brief Overview

- EPIGRIDS is developing methodologies to "grow" synthetic grid models, targeting OPF applications. We use algorithms that underlie historic expansion, representing impacts of population, spatial patterns of energy demand, geography, and land use on the growth of power systems.
- EPIGRIDS overviews previously presented in IEEE venues, including Sept 2016 ISGT in Minneapolis, MN. So today, we instead delve into project's progress on an alternative circuit modeling approach, intended to provide node-breaker detail for SCOPF that is rigorous, yet tractable.

Acknowledgement

- Today's presentation is based on work in collaboration with University of Wisconsin-Madison colleague Prof. **Michael Ferris**, PhD candidates **Byungkwon Park** & **Jayanth Netha**.

- The formulation here is being employed in construction of large-scale synthetic grid models, as part of the EPIGRIDS project under the ARPA-E GRID DATA, supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DEAR0000717.

- U.S. Dept. of Energy support is gratefully acknowledged; however, views and opinions of the author expressed in this presentation do not necessarily state or reflect those of the United States Government or any agency thereof.

IEEE PES Power & Energy Society®

IEEE

Modeling Approach

Two related ideas, each with a “revisionist” twist to adapt particularly to needs of Security Constrained OPF.

- **Component modeling**: Use multi-ports as ideal circuit elements in model, ***maintaining all element port voltages and currents as explicit variables in OPF***.
- **Network representation:** Abandon “Ybus,” with its strict nodal analysis. Advocate ***Sparse Tableau Analysis*** (STA) for network constraints with node-breaker detail.

Many more variables than traditional approaches, but even more sparse, and (initial experience suggests) often numerically better conditioned in OPF solution algorithms.

Traditional Models' Shortcomings

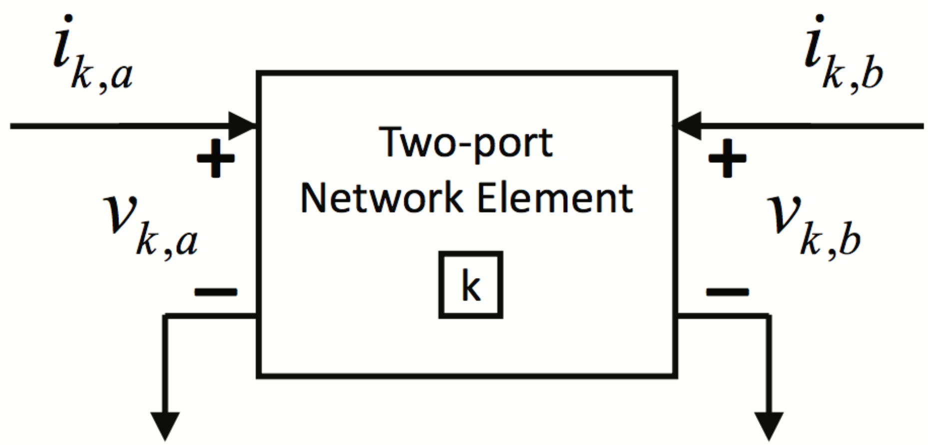
- Consider traditional power textbook's first analysis steps in modeling transmission lines:

  (i) Begin from pde's describing distributed behavior.
  (ii) Impose assumptions of balanced three phase operation, in sinusoidal steady state (SSS).
  (iii) Focus on relation between "sending end" and "receiving end" voltage-current pairs.

(BTW – these first steps are perfectly ok, when assumptions hold appropriately)

Transmission line as a two-port

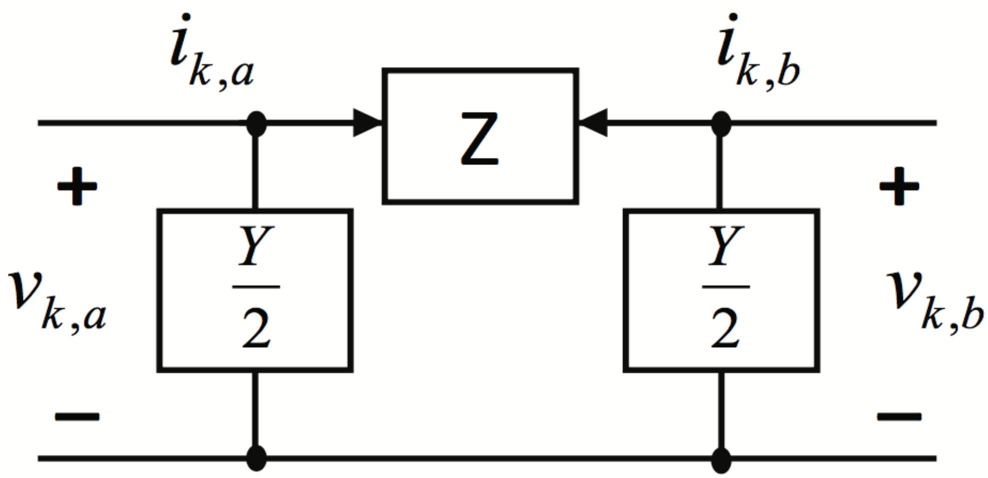
- Assumption (ii) provides per-phase algebraic relations; (iii) dictates structure of relation is **naturally** a two-port.



- The poor choice (IMO) of traditional power formulations occurs next: insistence on building equivalent circuit for two-port, constructed of strictly two-terminal admittances (instead: in power lingo, we keep the ABCD-matrix)

Limitations of the Pi-equivalent

- Existing approach in OPF chooses Y and Z, to match behavior of distributed model in steady state, at terminals.



- Shortcoming shows up in model validation: Otherwise reasonable-looking (Y, Z) can “fail the physics;” i.e., fail to match any plausible kmil conductor diameter, permeability, inter-phase conductor distance.

Ideal Transformer as a Two-Port

- An ideal transformer should be the poster-child for two-port analysis. For transformation gain "k," the two constitutive relations among the port variables are simply

$$v_b = kv_a,\ i_b=(1/k^*)i_a$$

(for phase shifting transformer, k may be complex)

- Today's practice in specifying power flow/OPF transformer data ***insists*** that non-zero series reactance be included, representing leakage flux.

- Why should an ideal transformer (no leakage reactance) be strictly prohibited by the way we specify our model?

IEEE PES Power & Energy Society®

IEEE

Ideal Transformer as a Two-Port

- Problem lies in the insistence on Ybus.
  Ybus requires that every component must have the property that the component's current(s) be expressible in terms of the component's voltage(s).

- In terminology of circuit analysis, we're demanding that ***EVERY*** component permits admittance representation.

- An ideal transformer does not have this property.

- And components of interest in future grid technologies may not either!

General Two-Port Representation

- In the a nonlinear case, with phasor quantities, a general two-port imposes two complex constraints on the four complex port variables, i.e.

$$f_k : \mathbb{C}^4 \longrightarrow \mathbb{C}^2$$

$$f_k(v_{k,a}, i_{k,a}, v_{k,b}, i_{k,b}) = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (1)$$

- For affine-linear case, most prevalent in power systems, write as: (for strictly linear, u_s=0)

$$F_v v + F_i i = u_s \quad (2)$$

- Ybus-based OPF formulation restricts to linear elements, ***with further restriction that F_i be invertible.***

Power & Energy Society®

The Role of Circuit Breakers

- Circuit breakers/disconnectors (i.e., switches) are ubiquitous throughout the power grid

- Lots of roles played by circuit breakers are NOT easily accommodated in Ybus; e.g. reconfiguration of substations after a contingency.

- Long recognized problem, addressed in such applications as State Estimation, but (IMO) less effectively addressed in OPF formulations.

The Role of Circuit Breakers

- Critiques of Ybus go way back; e.g. Alcir Monticelli's: "Modeling Zero Impedance Branches in Power System State Estimation," IEEE Trans on PS, v.6, n.4, 1991.

Abstract: This paper discusses the modeling of branches with zero impedances in power system state estimation. Such branches (short circuits) are commonly encountered in substation arrangements. Merging the terminal buses of the short circuit in a single bus may not be desirable for useful measurements would be lost. A common practice consists in modeling the series short circuits as a small impedance (usually an arbitrary value is adopted as the branch series impedance). In this paper a new modeling approach is introduced by means of which zero impedance branches can be modeled exactly. The proposed method is similar to the method used for representing zero injections as equality constraints. The main advantage of the proposed method is to eliminate one of the causes of ill-conditioning from state estimation matrices: the existence of adjacent branches presenting a wide range of impedance values.

The Role of Circuit Breakers

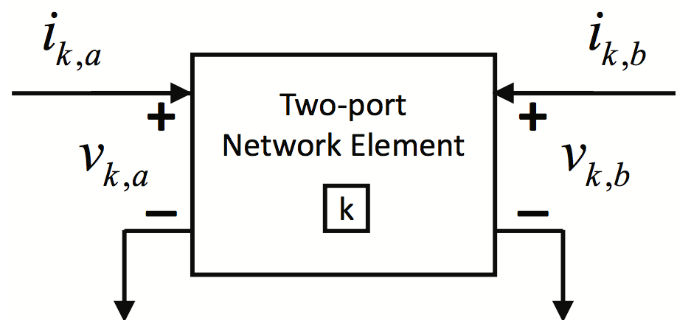
- Standard power flow/OPF models, based on strict nodal analyses, allow only node voltages as fundamental circuit variables. Hence, if a circuit breaker divides two sections of a busbar, a Ybus formulation must change dimension of model between the two breaker positions.

- "Topology processing" algorithms essentially rebuild a distinct Ybus admittance matrix for each configuration.

- Editorial comment: IMO, this is dumb. Opening or closing breaker **does not change network topology** – it changes the voltage/current behavior of **one element**!

ANOTHER Natural Two-Port

(i) breaker position indicated by binary variable γ;
(ii) maintain port voltage/current pairs as explicit variables;
(iii) as previously described, don't insist on F_i invertible.



$$\text{Circuit breaker closed, } \gamma = 1 : \begin{cases} v_a - v_b = 0 \\ i_a + i_b = 0 \end{cases}$$

$$\Longrightarrow \underbrace{\begin{bmatrix} 1 & -1 \\ 0 & 0 \end{bmatrix}}_{\mathbf{F}_v} \begin{bmatrix} v_a \\ v_b \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 \\ 1 & 1 \end{bmatrix}}_{\mathbf{F}_i} \begin{bmatrix} i_a \\ i_b \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Circuit Breaker Two-Port

$$\text{Circuit breaker open, } \gamma = 0 : \begin{cases} i_a = 0 \\ i_b = 0 \end{cases}$$

$$\Longrightarrow \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}}_{\mathbf{F}_v} \begin{bmatrix} v_a \\ v_b \end{bmatrix} + \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{\mathbf{F}_i} \begin{bmatrix} i_a \\ i_b \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

and as single description, in terms of γ:

$$\underbrace{\begin{bmatrix} \gamma & -\gamma \\ 0 & 0 \end{bmatrix}}_{\mathbf{F}_v} \begin{bmatrix} v_a \\ v_b \end{bmatrix} + \underbrace{\begin{bmatrix} (1-\gamma) & 0 \\ \gamma & 1 \end{bmatrix}}_{\mathbf{F}_i} \begin{bmatrix} i_a \\ i_b \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Network Constraints: KCL and KVL

- Observe that thus far we have described only the constitutive relations for a set of ideal elements. **These pertain to the elements themselves, independent of interconnection topology.**

- When elements are interconnected in a network, linear KCL and KVL constrain those elements' port currents and voltages, and relate them to nodal quantities:

  (i) node voltages, $\mathbf{V}$ (in the grid, busbar voltages);
  (ii) currents externally injected at nodes, $\mathbf{I}$;
  (these represent externally injected currents, supplied by generation, or withdrawn by load. Descriptions of $\mathbf{I}$ behavior to follow)

Network Constraints: KCL and KVL

- Familiar mechanism to express KCL and KVL in compact form is that of node-to-element incidence matrix, here denoted $\mathbf{A}$.

- Combining KCL, KVL, and linear constitutive relations, Sparse Tableau formulation is extraordinarily simple:

$$Ai = I$$

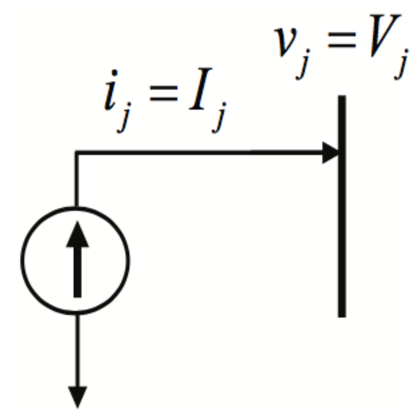
$$v = A^T V$$

$$F_v v + F_i i = 0$$

- If generation and load behaved as constant current sources/sinks, with fixed I, we'd be done now.

Generation and Load Behavior

- Each generator or load is a nonlinear controlled current sources, setting $\mathbf{I}$. Consider complex power at a bus, denoted $\mathbf{S}$, either as fixed parameter (e.g., load), or as decision variables to be solved via optimization (e.g, generator).



Then $I_j - \dfrac{S_j^*}{V_j^*} = 0$ or power balance form, $S_j = V_j I_j^*$

Experience with STF OPF

Sparse Tableau offers very simple (dare I say elegant?) formulation of OPF, as summarized below:

$$\min_{P,Q,v,i,V,I} \quad \sum_{j\in\mathbf{G}} \tilde{c}_j\left(P_{g,j}\right) \quad \text{subject to}$$

$$\begin{aligned}
\text{Linear Element:} \quad & F_v v + F_i i = 0 \\
\text{KCL:} \quad & I - Ai = 0 \\
\text{KVL:} \quad & v - A^T V = 0 \\
\text{Nonlinear Element:} \quad & S - V \odot (I)^* = 0 \\
\text{Gen. Limit:} \quad & P_j^{min} \leq P_{g,j} \leq P_j^{max} \\
& Q_j^{min} \leq Q_{g,j} \leq Q_j^{max}, \; \forall j \in \mathbf{G} \\
\text{Vol. Limit:} \quad & V_j^{min} \leq |V_j| \leq V_j^{max}, \; \forall j \in \mathbf{N} \\
\text{Line Limit:} \quad & |i_{k,a/b}|^2 \leq i_k^{max}, \; \forall k \in \mathbf{L}
\end{aligned}$$

Experience with STF OPF

- Experiments comparing Sparse Tableau to traditional Ybus OPF formulations are very preliminary, and to date have been performed only in the GAMS general purpose optimization environment, primarily with KNITRO solver.

- In several test systems from the MATPOWER distribution, up to several thousand buses, experience so far shows Sparse Tableau very comparable in speed.

Experience with STF OPF

	POLAR-Y_{bus}		REC-IV-Y_{bus}		REC-STF	
	Obj	Time	Obj	Time	Obj	Time
case118	129660.68	0.3sec	129660.68	0.3sec	129660.68	0.3sec
case300	719725.07	0.6sec	719725.07	2sec	719725.07	0.6sec
case2383wp	1868511.82	5.6sec	1862367.02	5.2sec	1862367.02	6.3sec
case3012wp	2591706.57	5.8sec	2582670.47	5.9sec	2582670.47	6sec
case3120sp	2142703.76	5.8sec	2141532.10	6.3sec	2141532.10	6.5sec
case3375wp	7412030.67	54sec	7404635.99	11.7sec	7404637.15	11.4sec

Take Away Points

- Many parts of power grid transmission network are fundamentally simple circuits, often linear.

- Many of the historic “tricks”/reductions in power grid model formulations are arguably becoming less advantageous, because of advances in computational tools, and because new component technologies undermine assumptions needed for these shortcuts.

- Sparse Tableau formulation facilitates model construction that is versatile and consistent with node-breaker detail, allowing model to easily capture substation reconfiguration in contingencies. In first experiments, it is just as fast as traditional Ybus.