Log(v) 3LPF: A linearized solution to train reinforcement learning algorithms for distribution systems

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Reinforcement learning on distribution systems, PPO-Clip

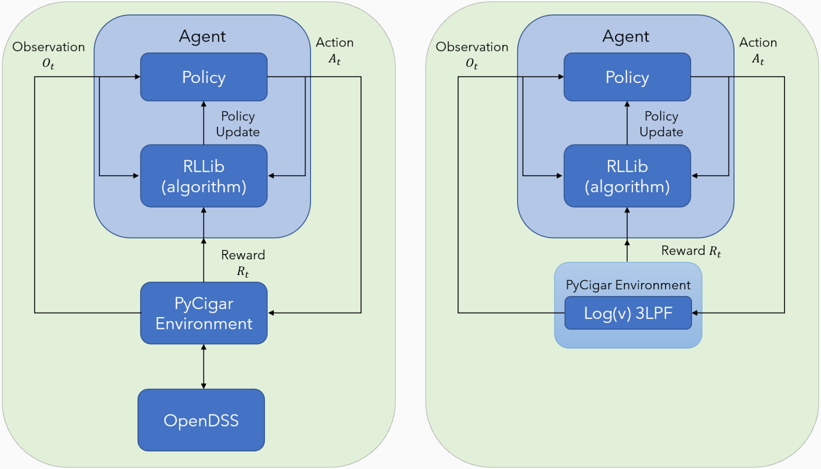


Figure 1: Current PyCigar modeling diagram (left) vs proposed architecture (right)

Reinforcement learning on distribution systems, PPO-Clip

- Two neural networks. Weights obtained via SGD
  - Policy function: $\theta_{k+1} = \arg\min_\theta g(\hat{R}_t, s_{rl}, a_{rl}, \theta)$
  - Value function: $\phi_{k+1} = \arg\min_\phi h(\hat{R}_t, s_{rl}, a_{rl}, \phi)$
- Power Flow (PF) equations are used to compute the rewards
- Rewards are computed for every training iteration, every time step and every action sampled by the algorithm
- **Efficient** and **accurate** PF solvers are necessary

Our target: $\rightarrow \boxed{\hat{R}_t = f({s_p}^1, {s_{rl}}^2, {a_{rl}}^3)}$

[1] s_p: Power system state
[2] s_{rl}: Reinforcement learning state
[3] a_{rl}: Reinforcement learning action

Distribution systems are unbalanced

- Unbalanced system $\rightarrow$ 3-phase solvers
- Need for AC modeling vs DC
  - AC PF equations are **non-linear**
  - Non-linearity is caused by ZIP load models (details later)
- Modeling of line losses through shunt elements (not negligible) needed

PF formulations:

Current: $\boldsymbol{i} = \boldsymbol{Y}_{\text{bus}} \boldsymbol{v}$

Power: $\boldsymbol{s} = D(\boldsymbol{v}\boldsymbol{v}^H \boldsymbol{Y}_{\text{bus}}^H)$

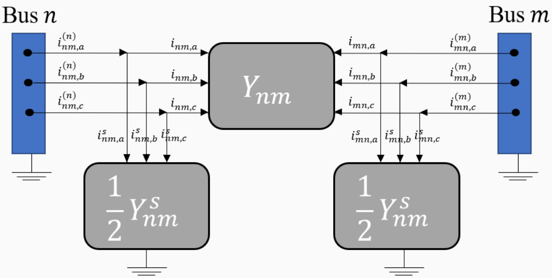


Figure 2: Pi-Model representation

Survey of ACPF solvers

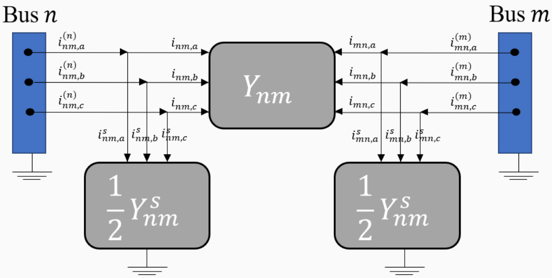
- Commercial software PF solvers are **iterative**
  - Newton-Raphson (GridLab-D, PSLF)
  - Gauss-Seidel (OpenDSS,GridLab-D)
  - Forward-Backward Sweep (GridLab-D)
- Previous work, linear approximations
  - Lin3DistFlow [Sankur et al., 2016]. Nominal voltages and no losses. No ZIP models
  - NFA [Fobes et al., 2020]. Real-power only, no ZIP models
  - DCP [Fobes et al., 2020]. DC assumption, ignores reactive power, no ZIP models
  - Lossy Distflow [Schweitzer et al., 2019]. Not valid for complete ZIP models, cannot acommodate modeling of transformers, regulators, losses are parametrized.
  - **LPF** [Li et al., 2017]. Positive-sequence only, lossless, no ZIP models, doesn't exploit tree structure (use case is transmission systems).

Our contribution

- **Modeling capabilities**
    - Embedded linear power flow solver
    - ZIP load models, shunt capacitors, regulators, transformers, smart inverters, batteries, and corresponding controls (as of today).
    - Ability to fully control and understand unbalanced 3-phase distribution systems. Implementation of new attack vectors
    - Linear PF and OPF. Applicable to transmission systems.
- **Modeling accuracy**
    - PF solution validated against OpenDSS
    - Modeling of devices matches that of OpenDSS
- **Computational complexity**
    - Linear equations allow to solve the system in a single snapshot. In OpenDSS, IEEE-13 11 iterations, IEEE-8500 62 iterations reducing RL training times
    - Ability to exploit graph tree structure
    - Ability to efficiently compute inverse after perturbation
    - Reduced overhead due to api calling external models

Log(v) 3LPF

Log(v) 3LPF



Kirchoff: $\boldsymbol{i}_{nm}^{(n)} = \boldsymbol{i}_{nm} + \boldsymbol{i}_{nm}^s$

Ohm: $\boldsymbol{i}_{nm} = \mathrm{Y}_{nm}^{(n)}\boldsymbol{v}_n - \mathrm{Y}_{nm}^{(m)}\boldsymbol{v}_m$

Losses: $\boldsymbol{i}_{nm}^s = \frac{1}{2}\mathrm{Y}_{nm}^s\boldsymbol{v}_n$

$$\boldsymbol{i}_{nm}^{(n)} = \left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2}\mathrm{Y}_{nm}^s\right)\boldsymbol{v}_n - \mathrm{Y}_{nm}^{(m)}\boldsymbol{v}_m$$

$$\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n\left(\boldsymbol{i}_{nm}^{(n)}\right)^H$$

$$\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n\boldsymbol{v}_n^H\left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2}\mathrm{Y}_{nm}^s\right)^H - \boldsymbol{v}_n\boldsymbol{v}_m^H\left(\mathrm{Y}_{nm}^{(m)}\right)^H$$

Log(v) 3LPF

$$\boxed{\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n \boldsymbol{v}_n^H \left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2} \mathrm{Y}_{nm}^{s} \right)^H - \boldsymbol{v}_n \boldsymbol{v}_m^H \left(\mathrm{Y}_{nm}^{(m)} \right)^H}$$

We want to remove the non-linearity $\boldsymbol{v}_n \boldsymbol{v}_n^H$ from the equation that relates power flows to voltage

$$\boldsymbol{v}_n := \left[v_n^a, v_n^b, v_n^c \right]^T, \quad v_n^p = |v_n^p| \, e^{j\theta_p} \tag{1}$$

$$|v_n^p| = e^{\log|v_n^p|}, \quad u_n^p := \log |v_n^p| \tag{2}$$

$$\boxed{v_n^p = e^{u_n^p} e^{j\theta_p}} \tag{3}$$

Log(v) 3LPF

$$\boxed{\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n \boldsymbol{v}_n^H \left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2} \mathrm{Y}_{nm}^{s} \right)^H - \boldsymbol{v}_n \boldsymbol{v}_m^H \left(\mathrm{Y}_{nm}^{(m)} \right)^H}$$

We know voltages are around 1 p.u., thus $\log(1) = 0$, and we approximate the voltage magnitude in $v_n^p = e^{u_n^p} e^{j\theta_p}$ using first-order Taylor expansion.

$$\boldsymbol{v}_n := \begin{pmatrix} e^{u_n^a} e^{j\theta_n^a} \\ e^{u_n^b} e^{j\theta_n^b + \frac{2\pi}{3} - \frac{2\pi}{3}} \\ e^{u_n^c} e^{j\theta_n^c - \frac{2\pi}{3} + \frac{2\pi}{3}} \end{pmatrix} = \boldsymbol{\Delta}_3 \mathrm{diag} \begin{pmatrix} e^{u_n^a} \\ e^{u_n^b} \\ e^{u_n^c} \end{pmatrix} \begin{pmatrix} e^{j\tilde{\theta}_n^a} \\ e^{j\tilde{\theta}_n^b} \\ e^{j\tilde{\theta}_n^c} \end{pmatrix} \tag{4}$$

$$\boldsymbol{v}_n \approx \boldsymbol{\Delta}_3 \left(\mathrm{I} + \mathrm{diag}\left(\boldsymbol{u}_n \right) \right) e^{j\tilde{\boldsymbol{\theta}}_n} \tag{5}$$

$$\begin{aligned} \boldsymbol{v}_n \boldsymbol{v}_n^H &\approx \boldsymbol{\Delta}_3 \left(1 1^T + \boldsymbol{u}_n 1^T + 1^T \boldsymbol{u}_n^T + \mathrm{j} \tilde{\boldsymbol{\theta}}_n 1^T - \mathrm{j} 1 \tilde{\boldsymbol{\theta}}_n^T \right) \boldsymbol{\Delta}_3^H \\ \boldsymbol{v}_n \boldsymbol{v}_m^H &\approx \boldsymbol{\Delta}_3 \left(1 1^T + \boldsymbol{u}_n 1^T + 1^T \boldsymbol{u}_m^T + \mathrm{j} \tilde{\boldsymbol{\theta}}_n 1^T - \mathrm{j} 1 \tilde{\boldsymbol{\theta}}_m^T \right) \boldsymbol{\Delta}_3^H \end{aligned} \tag{6}$$

Log(v) 3LPF

Non-linear ACPF: $\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n \boldsymbol{v}_n^H \left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2} \mathrm{Y}_{nm}^{s} \right)^H - \boldsymbol{v}_n \boldsymbol{v}_m^H \left(\mathrm{Y}_{nm}^{(m)} \right)^H$

Reordering and defining the corresponding matrices and vectors

Log(v) 3LPF (Linear):

$$\tilde{\boldsymbol{s}}_{nm} \approx \tilde{\mathrm{Y}}_{\text{bus}} \boldsymbol{x} \quad \text{where} \quad \boldsymbol{x} \triangleq \begin{bmatrix} \boldsymbol{u} \\ \tilde{\boldsymbol{\theta}} \end{bmatrix} \tag{7}$$

$$\boldsymbol{x} \approx \tilde{\mathrm{Y}}_{\text{bus}}^{-1} \tilde{\boldsymbol{s}}_{nm}$$

and we may recover the voltage phasors as follows

$$\boldsymbol{v} \approx \boldsymbol{\Delta}_3 \mathrm{diag}\left(e^{\boldsymbol{u}}\right) e^{j\tilde{\boldsymbol{\theta}}_n}$$

ZIP models

ZIP models. Wye-connected loads

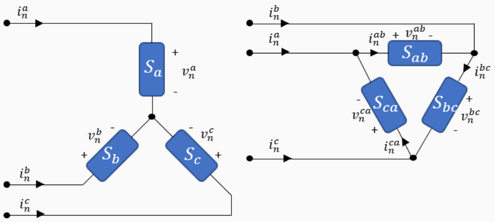


Figure 3: Wye (left) and delta-connected (right) load

Wye-connected loads: $\mathsf{S}_n^{\mathsf{Y}} = \mathsf{S}_n^{\mathsf{Z,Y}} + \mathsf{S}_n^{\mathsf{I,Y}} + \mathsf{S}_n^{\mathsf{P,Y}}$

Z: $\mathsf{S}_n^{\mathsf{Z,Y}} = \left(\mathsf{y}_n^{\mathsf{Y}}\right)^* + 2\mathrm{diag}(\mathsf{y}_n^{\mathsf{Y}})^* \boldsymbol{u}_n$

I: $\mathsf{S}_n^{\mathsf{I,Y}} \approx \boldsymbol{\Delta}_3 \left(\boldsymbol{i}_n^{\mathsf{Y}}\right)^* + \boldsymbol{\Delta}_3 \mathrm{diag}\left(\boldsymbol{i}_n^{\mathsf{Y}}\right)^* \boldsymbol{u}_n + \mathrm{j}\boldsymbol{\Delta}_3 \mathrm{diag}\left(\boldsymbol{i}_n^{\mathsf{Y}}\right)^* \tilde{\boldsymbol{\theta}}_n$

P: $\mathsf{S}_n^{\mathsf{P,Y}} = \mathsf{s}_\ell^{\mathsf{Y}}$

ZIP models. Delta-connected loads

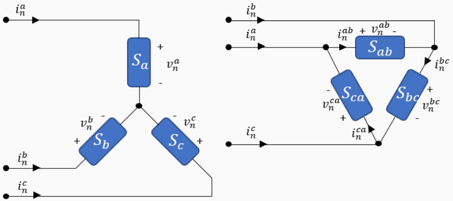


Figure 4: Wye (left) and delta-connected (right) load

Delta-connected loads: $\mathsf{S}_n^{\boldsymbol{\Delta}} = \mathsf{S}_n^{\mathsf{Z},\Delta} + \mathsf{S}_n^{\mathsf{I},\Delta} + \mathsf{S}_n^{\mathsf{P},\Delta}$

Z: $$\mathsf{S}_n^{\mathsf{Z},\Delta} \approx \left(\mathrm{diag}\left(\boldsymbol{\Delta}_3 \left(\tilde{\mathsf{Y}}_n^{\boldsymbol{\Delta}}\right)^T 1\right) + \boldsymbol{\Delta}_3 \left(\tilde{\mathsf{Y}}_n^{\boldsymbol{\Delta}}\right)^T\right) \boldsymbol{u}_n + \left(\mathrm{diag}\left(\boldsymbol{\Delta}_3 \left(\tilde{\mathsf{Y}}_n^{\boldsymbol{\Delta}}\right)^T 1\right) - \boldsymbol{\Delta}_3 \left(\tilde{\mathsf{Y}}_n^{\boldsymbol{\Delta}}\right)^T\right) \tilde{\boldsymbol{\theta}}_n$$

I: $$\mathsf{S}_n^{\mathsf{I},\Delta} \approx \boldsymbol{\Delta}_3 \boldsymbol{\Lambda} \left(\boldsymbol{i}_n^{\mathsf{Y}}\right)^* + \boldsymbol{\Delta}_3 \mathrm{diag}\left(\boldsymbol{\Lambda} \boldsymbol{i}_n^{\mathsf{Y}}\right)^* \boldsymbol{u}_n + \mathrm{j} \boldsymbol{\Delta}_3 \mathrm{diag}\left(\boldsymbol{\Lambda} \boldsymbol{i}_n^{\mathsf{Y}}\right)^* \tilde{\boldsymbol{\theta}}_n$$

P: $$\mathsf{S}_n^{\mathsf{P},\Delta} \approx \boldsymbol{\Lambda} \mathsf{s}_\ell^{\Delta}$$

Modeling and control of power delivery elements

Transformers and voltage regulators

Modeled through the **admittance matrix**

$$\boldsymbol{S}_{nm}^{(n)} = \boldsymbol{v}_n \boldsymbol{v}_n^H \left(\mathrm{Y}_{nm}^{(n)} + \frac{1}{2}\mathrm{Y}_{nm}^{s} \right)^H - \boldsymbol{v}_n \boldsymbol{v}_m^H \left(\mathrm{Y}_{nm}^{(m)} \right)^H$$

Transformers:

$$\mathrm{Y}_{\text{prim}} = \mathrm{ANB}\left(\mathrm{Z}_{nm}^{t}\right)^{-1} \mathrm{B}^{\mathrm{T}}\mathrm{N}^{\mathrm{T}}\mathrm{A}^{\mathrm{T}}$$

$$\mathrm{Y}_{\text{prim}} = \begin{pmatrix} \mathrm{Y}_{nm}^{(n)} & \mathrm{Y}_{nm}^{(m)} \\ \mathrm{Y}_{mn}^{(n)} & \mathrm{Y}_{mn}^{(m)} \end{pmatrix}$$

Voltage regulators:

$$\mathrm{Y}_{\text{prim}} = \boldsymbol{\Gamma}\mathrm{ANB}\left(\mathrm{Z}_{nm}^{t}\right)^{-1} \mathrm{B}^{\mathrm{T}}\mathrm{N}^{\mathrm{T}}\mathrm{A}^{\mathrm{T}}\boldsymbol{\Gamma}^{\mathrm{T}}$$

where $\boldsymbol{\Gamma} = \mathrm{diag}\left(\boldsymbol{\gamma}\right)$ and $\gamma_i = 1 \pm 0.00625\tau_i$

$$\tau_i = f\left(v_{\text{reg}}, v_b, v_n\right)$$

Attack vectors

v_{reg} setpoint, v_b bandwidth, v_n measurement

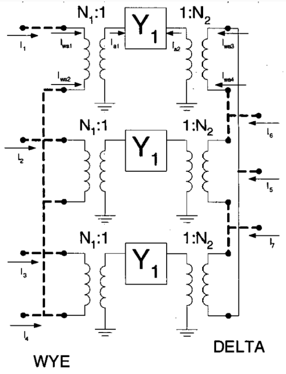


Figure 5: WyeG-Delta Transformer

Shunt capacitors and cap controls

Modeled as a wye or delta-connected **constant impedance load**

$$\boxed{\mathsf{S}_n^{\mathsf{Z},\mathsf{Y}} = \mathsf{D}\left(\boldsymbol{v}_n \boldsymbol{v}_n^H \boldsymbol{\Pi} \left(\mathsf{Y}_n^{\mathsf{Y}}\right)^H \boldsymbol{\Pi}^T\right)} \quad \text{or} \quad \boxed{\mathsf{S}_n^{\mathsf{Z},\Delta} = \mathsf{D}\left(\boldsymbol{v}_n \boldsymbol{v}_n^H \boldsymbol{\Pi} \left(\mathsf{Y}_n^{\boldsymbol{\Delta}}\right)^H \boldsymbol{\Pi}^T\right)}$$

Capacitor banks:

$$\mathsf{Y}_n^{\mathsf{Y}} = \operatorname{diag}\left(\mathsf{y}_n^{\mathsf{Y}}\right), \mathsf{Y}_n^{\boldsymbol{\Delta}} = \operatorname{diag}\left(\mathsf{y}_n^{\boldsymbol{\Delta}}\right),$$

$$\mathsf{y}_n^{\mathsf{Y}} = \left[\mathsf{y}_{n,a}^{\mathsf{Y}}, \mathsf{y}_{n,b}^{\mathsf{Y}}, \mathsf{y}_{n,c}^{\mathsf{Y}}\right]^T, \mathsf{y}_n^{\boldsymbol{\Delta}} = \left[\mathsf{y}_{n,a}^{\boldsymbol{\Delta}}, \mathsf{y}_{n,b}^{\boldsymbol{\Delta}}, \mathsf{y}_{n,c}^{\boldsymbol{\Delta}}\right]^T$$

Cap controls:

$$\mathsf{y}_n^{\mathsf{Y}} = \sum_{i=1}^{n_c^s} \eta_{c,i} \mathsf{y}_{c,i}^{\mathsf{Y}}, \quad \mathsf{y}_n^{\boldsymbol{\Delta}} = \sum_{i=1}^{n_c^s} \eta_{c,i} y_{c,i}^{\boldsymbol{\Delta}}$$

$$\text{where} \quad n_c^s \to \text{N steps}, \quad \eta_{c,i} \in \{0,1\} \quad \eta_{c,i} = f(\vartheta^4, \boxed{\overline{\vartheta}, \underline{\vartheta}^5})$$

[4]Control input (current, voltage, kvar, PF, time)

[5]Attack vector. Upper and lower limits (operation is outside limits)

DER and smart inverters

Modeled as a wye-connected **constant power load**

$$\boxed{\mathsf{S}_n^{\mathsf{P},\mathsf{Y}}(t) = \mathsf{s}_\ell^{\mathsf{Y}}(t)}$$

Solar resources and batteries:

$$\mathsf{S}_n^{\mathsf{P},\mathsf{Y}}(t) = \mathsf{s}_\ell^{\mathsf{Y}}(t) \quad \text{and} \quad \mathsf{S}_n^{\mathsf{P},\mathsf{Y}}(t) = f(\eta_{c,t}, \eta_{d,t}, s_{oc}(t-1)^6)$$

Smart Inverters:

$$\mathsf{S}_n^{\mathsf{P},\mathsf{Y}}(t) = \boxed{f(\mathsf{s}_\ell^{\mathsf{Y}}(t-1), v_{n,t}{}^7)}^8$$

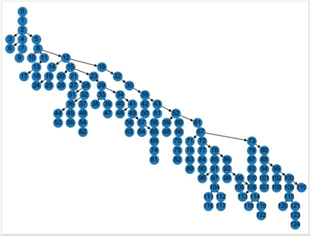
[6] State of charge

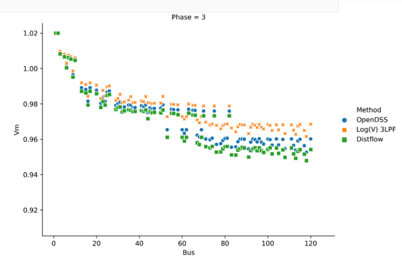
[7] Voltage measurement

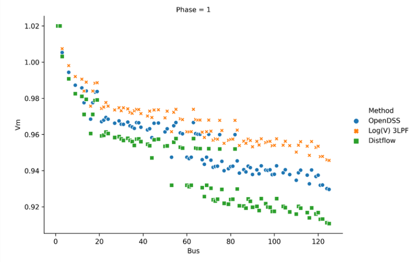
[8] Attack vector. Changes in drop curve settings

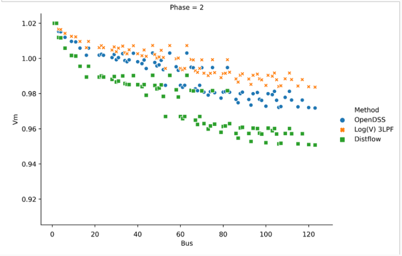
Preliminary results

IEEE-123 test case









OpenDSS vs Log(V) 3LPF

RMSE (IEEE-123)	Distflow	Log(V) 3LPF
Phase 1	0.014	0.012
Phase 2	0.016	0.08
Phase 3	0.006	0.04

Case	Devices	Buses	Nodes	Losses (%)
IEEE-123	238	132	278	2.63
IEEE-8500	7282	4876	8531	10.58
European LV	965	907	2721	0.2703

Case	Iterations	OpenDSS (s)	Log(V) 3LPF (s)
IEEE-123	3	0.011	0.001
IEEE-8500	62	0.244	n/a
European LV	3	0.087	n/a

Current efforts. Future work

- Exploring techniques to solve the linear system of equations. E.g.
    - Forward-backward sweep
    - Truncated SVD
    - Parallel computation on leaf nodes
- Re-centering around 1 to obtain better approximation
- Sherman-Morrison for matrix inversion after perturbation
- Solving large cases directly from .dss files

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