Leveraging Conservation Voltage Reduction for Energy Efficiency, Demand Side Control and Voltage Stability Enhancement in Integrated Transmission and Distribution Systems

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Project Introduction

Leveraging Conservation Voltage Reduction for Energy Efficiency, Demand Side Control and Voltage Stability Enhancement in Integrated Transmission and Distribution Systems

Power Systems Engineering Research Center (PSERC Project # S-70)

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Project Summary

- ***Project Definition***: We propose a comprehensive framework that assesses energy saving, demand reduction and stability enhancement potential of conservation voltage reduction (CVR).
- ***Project Goals:***

✓ Assess real-time real/reactive load-reduction effects of CVR based on load modeling

✓ Investigate mutual impacts between voltage reduction and voltage control of DGs

✓ Analysis of local VVC and hybrid VVC

✓ Develop a co-simulation framework for transmission and distribution systems to investigate CVR's impacts on transmission system load margin

✓ Develop a distributed multi-objective optimization model to coordinate the fast-dispatch of photovoltaic (PV) inverters with the slow-dispatch of voltage regulators for implementing CVR in unbalanced three-phase distribution systems

This integrated framework will facilitate utilities to select feeders for voltage reduction, to perform cost/benefit analyses, to reduce the stress of transmission systems, and to improve the operations of feeders under high-level renewable penetration.

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ISU

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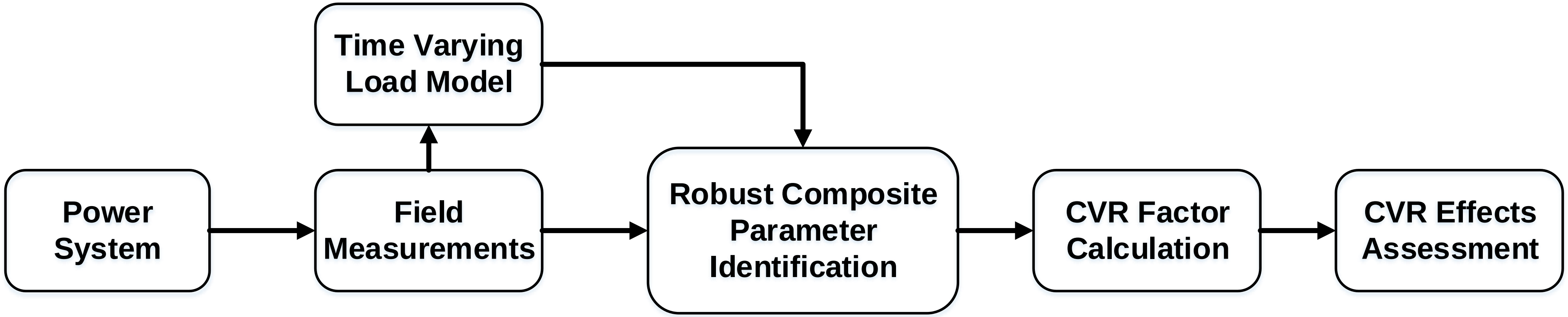
Proposed Robust CVR Assessment Method

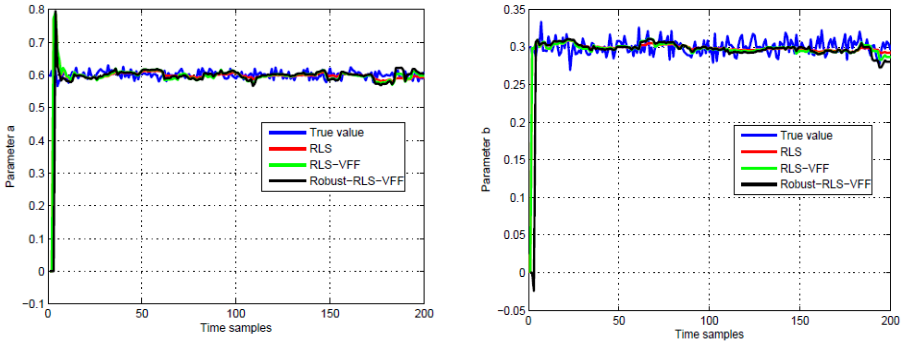
- This work aims to propose a robust time varying load modeling technique for CVR assessment.
- Load is represented as a ZIP model with time varying parameters.
- Robust recursive least squares method with variable forgetting factor (Robust-RLS-VSF) is proposed.
- The measurement devices, like RTU, smart meters, are installed at substation to continuously monitor power system operations and collect real and reactive power and voltage.
- After the modeling of time varying loads, the filed measurements are used as inputs for the proposed RRLS estimator to identify load parameters.
- The derived CVR factor of the stochastic loads in then calculated, followed by the statistical analysis of the CVR effects.



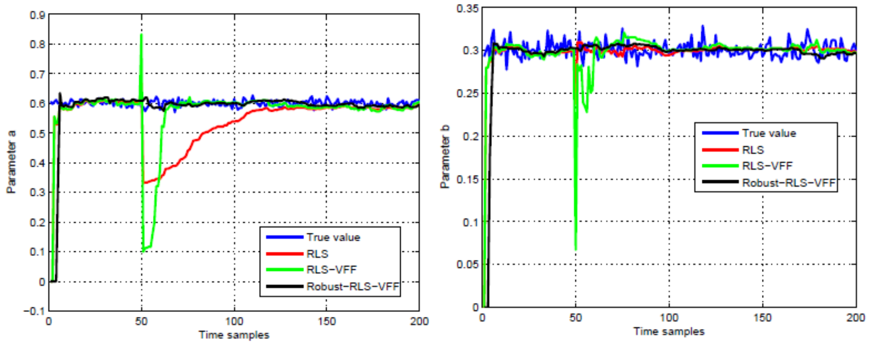
Case Study with the Estimated Load Parameter

- The effectiveness and robustness of the proposed robust time varying parameter identification method is evaluated on IEEE 118-bus test system with simulated data under various operating conditions.

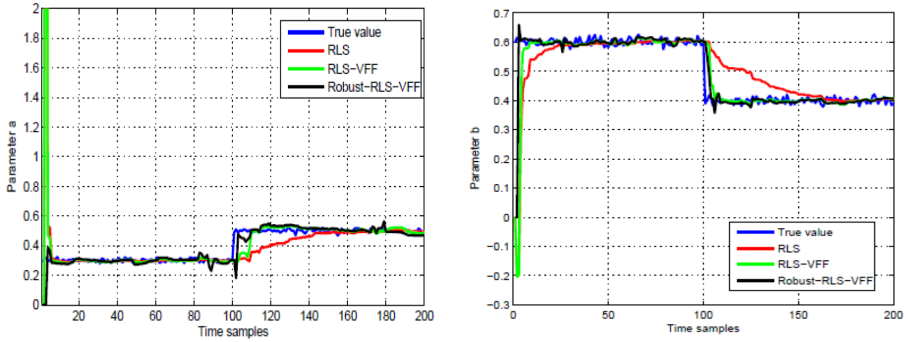
- Case 1 **Continuous Change in Load Parameters**



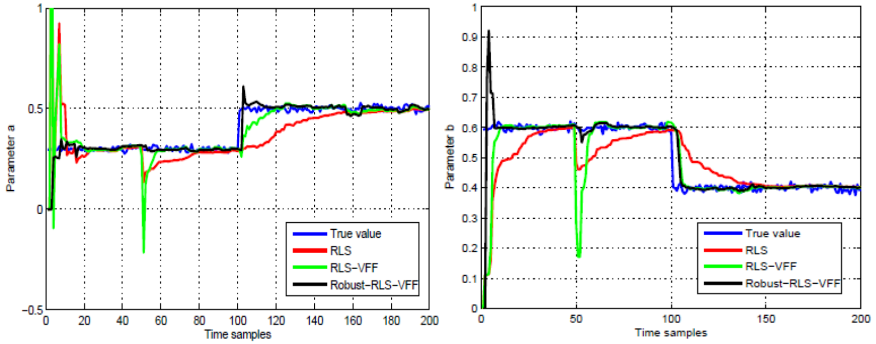
- Case 3 **With outliers in Load Parameters**



- Case 2 **With Step Change in Load Parameters**



- Case 4 **With both step change and outliers in Load Parameters**

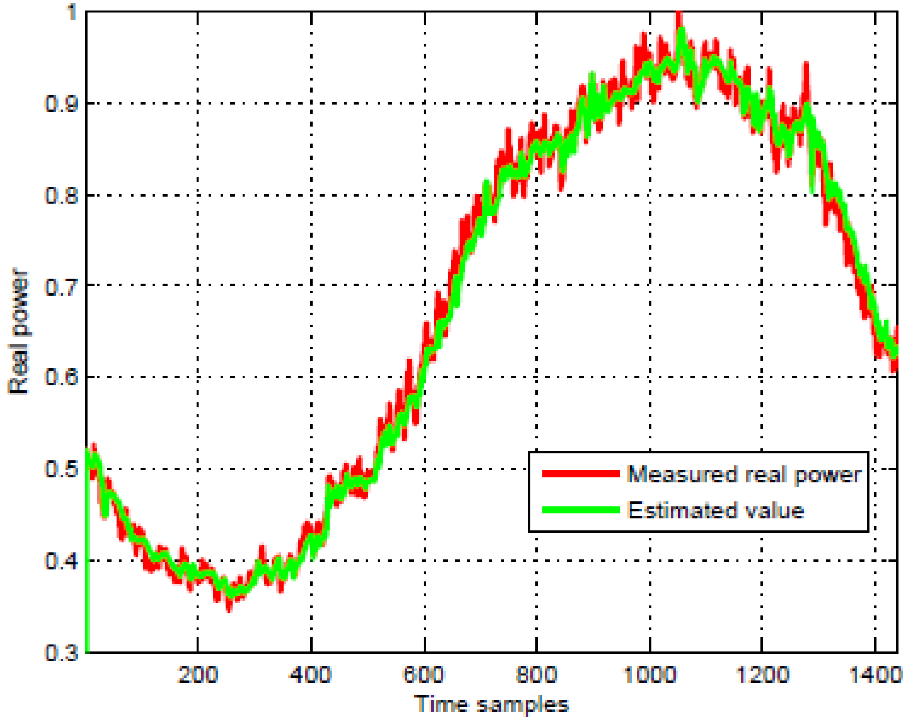


True value RLS RLS-VFF Robust-RLS-VFF

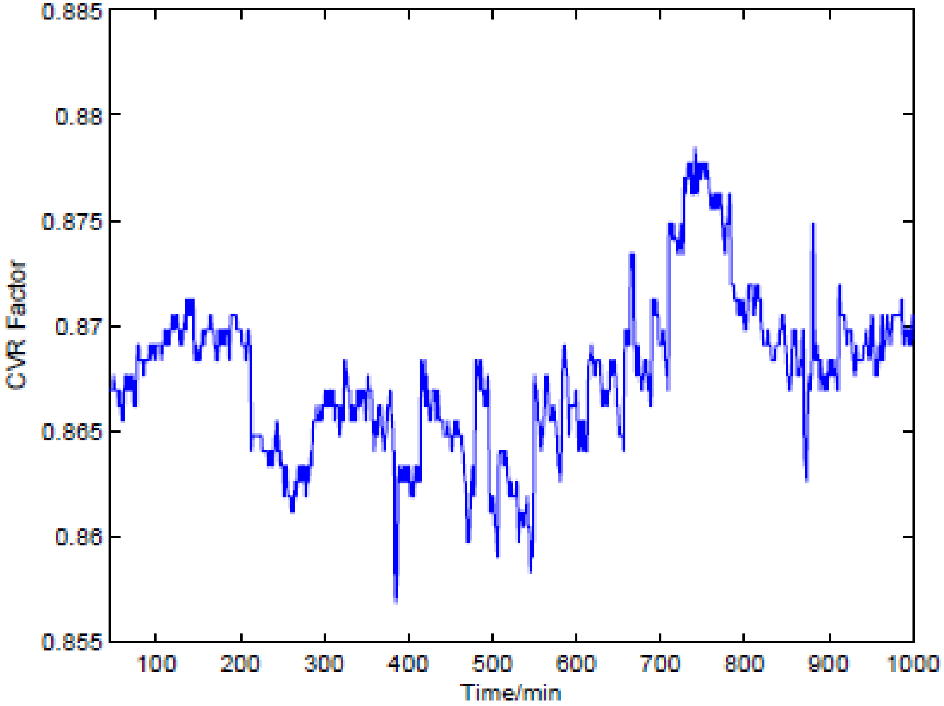
Application for CVR Assessment

- The Robust-RLS-VSF is applied for CVR assessment using field measurement from a substation of utility company.

  - Comparison results of the estimated and the measured active power



  - CVR factors during voltage reduction period



- The active power CVR factor:

$$CVR_{factor} = \frac{\%\Delta P}{\%\Delta V}$$

- Online load model parameter identification is needed to assess CVR effects

Impact of CVR on Substation VAR w/ and w/o Solar Power

CVR Impact Study :

- Impact of CVR on feeder reactive power (VAR) with and without solar
- IEEE 34 bus system with ZIP (0.4 0.3 0.3)
- Solar PV added at 3 nodes (890, 860, 840) ≈21.1 % of total load
- CVR is performed here at peak load

Substation Voltage

	Before CVR	After CVR
No Solar	1	0.97
Solar	1	0.97

w/o Solar

Case	P (Real Power) Before CVR	P (Real Power) After CVR	P (Real Power) Change (%)	Q (Reactive Power) Before CVR	Q (Reactive Power) After CVR	Q (Reactive Power) Change (%)
Substation (MW/MVAR)	2.38	2.29	3.70	1.11	1.09	1.89
Losses (kW/KVAR)	512.67	507.55	1.00	339.62	336.20	1.01
Load (MW/MVAR)	1.86	1.78	4.44	0.77	0.76	2.28

w/ Solar (unity power factor)

Case	P (Real Power) Before CVR	P (Real Power) After CVR	P (Real Power) Change (%)	Q (Reactive Power) Before CVR	Q (Reactive Power) After CVR	Q (Reactive Power) Change (%)
Substation (MW/MVAR)	1.91	1.84	3.72	0.98	0.96	1.91
Losses (kW/KVAR)	307.4	304.6	0.93	202.05	200.17	0.93
Load (MW/MVAR)	1.61	1.54	4.26	0.78	0.76	2.16

T&D Co-Simulation Framework

$$G_T(x_T^{k-1}, S_S^{k-1})^k = 0$$ ← Transmission Powerflow

⬇

V_S^k, θ_S^k (Substation Voltage)

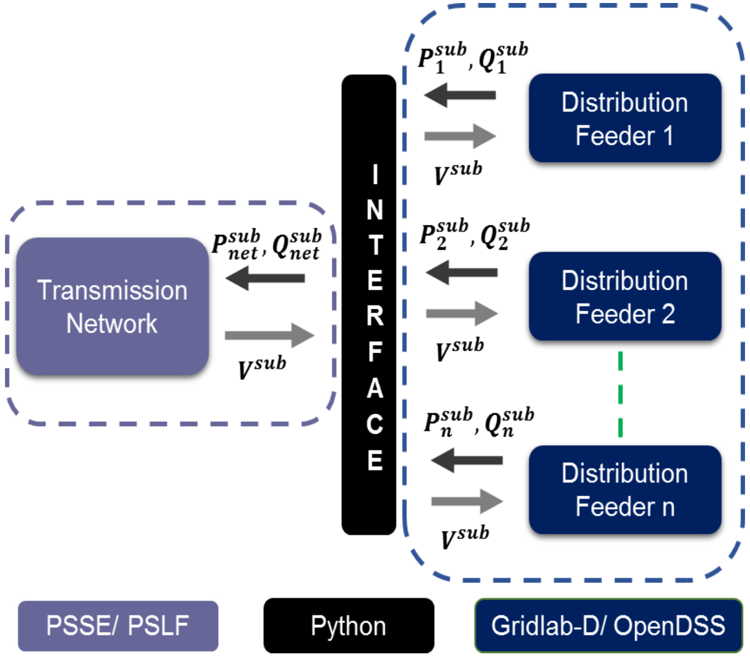
$$G_D(x_D, (V_S^k, \theta_S^k))^k = 0$$ ← Distribution Powerflow (3-Ø unbalanced)

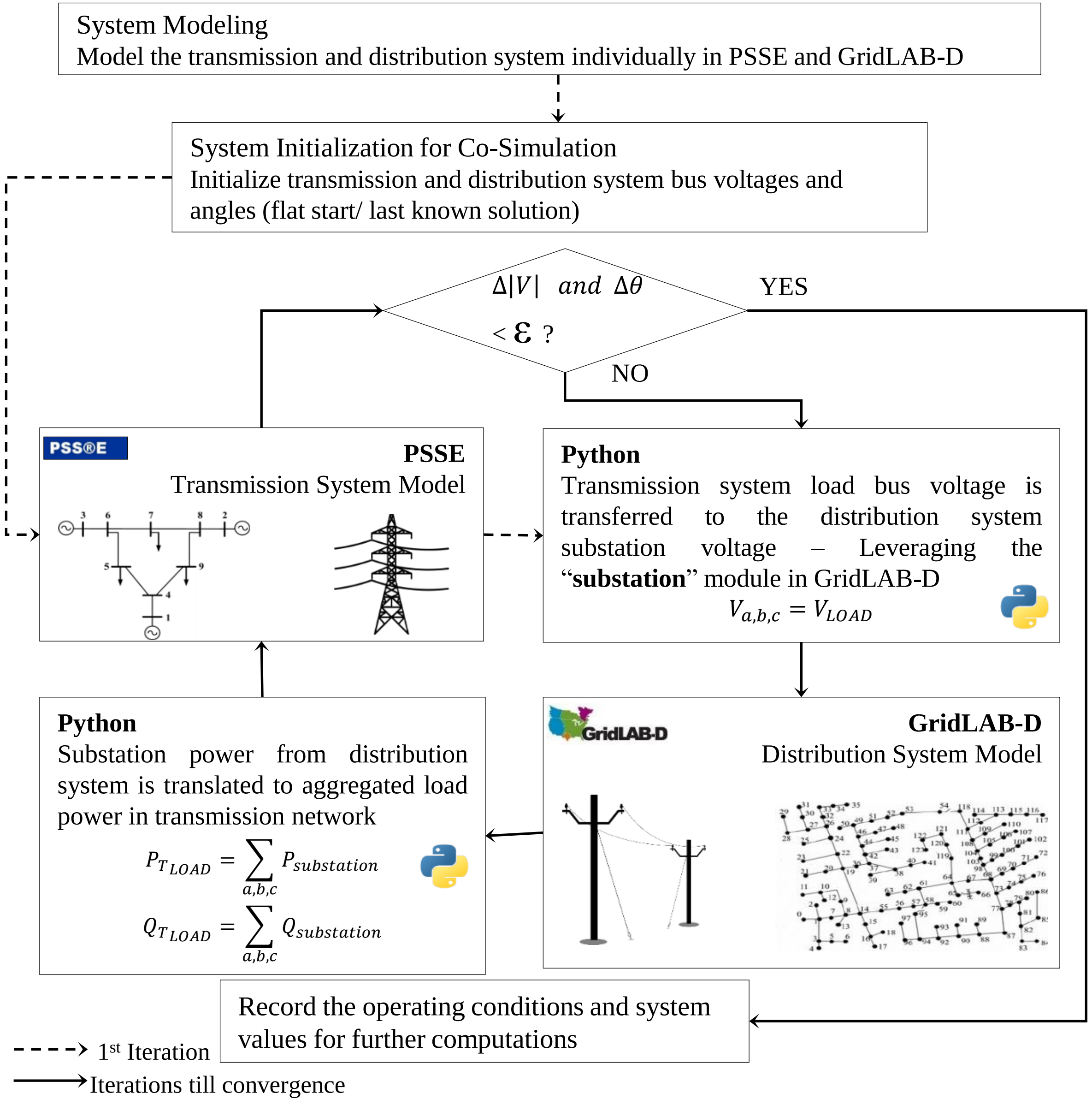
⬇

$$S_A^k, S_B^k, S_C^k$$

$$S_S^k = S_A^k + S_B^k + S_C^k$$

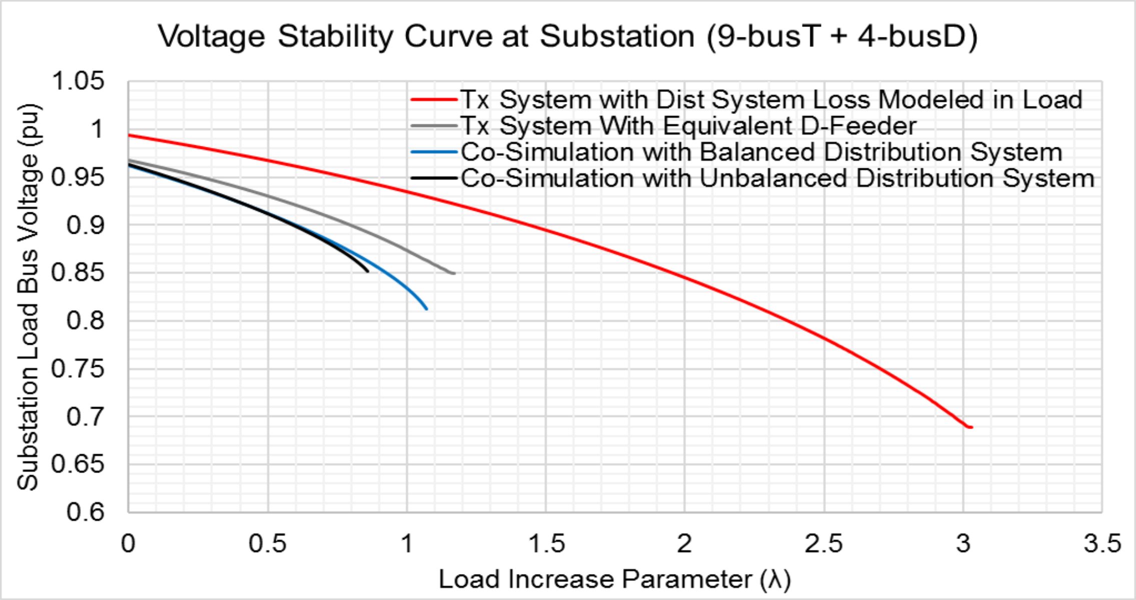
This is repeated till $|V_S^k - V_S^{k-1}| < \epsilon$





Importance of Modeling the Distribution System

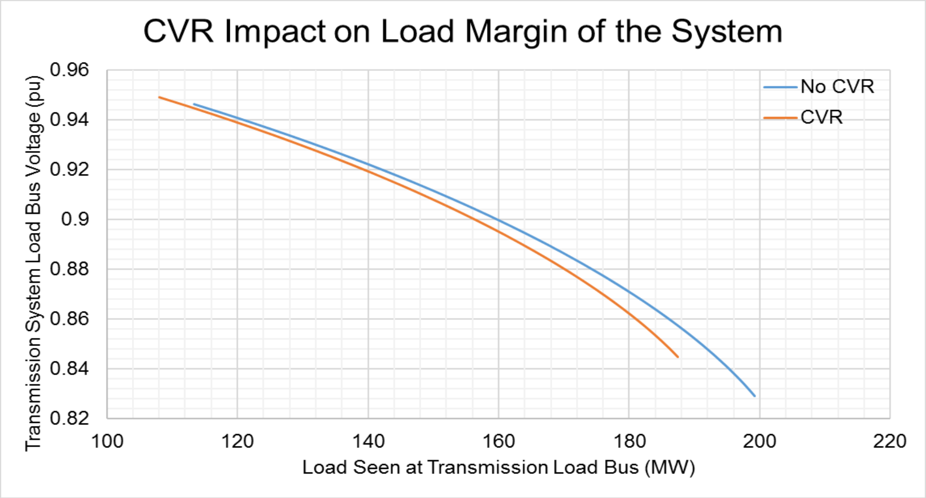
System Characteristics	**Transmission System with Dist. Loss modeled in Load**	**Transmission System With equivalent D- Feeder**	**Only Distribution System**	**T&D Co-Simulation**
Distribution Losses	✓	✓	✓	✓
Feeder Voltage drop	✘	✓	✓	✓
Impact of feeder voltage drop	✘	✘	✓	✓
Unbalance in Distribution	✘	✘	✓	✓
Effect of Transmission System	✘	✓	✘	✓



- Distribution system limits the system margin
- Equivalent distribution feeder model is effective but doesn't capture unbalance
- Co-simulation is an effective methodology to capture the effect of unbalance in distribution network

Impact of CVR on Load Margin

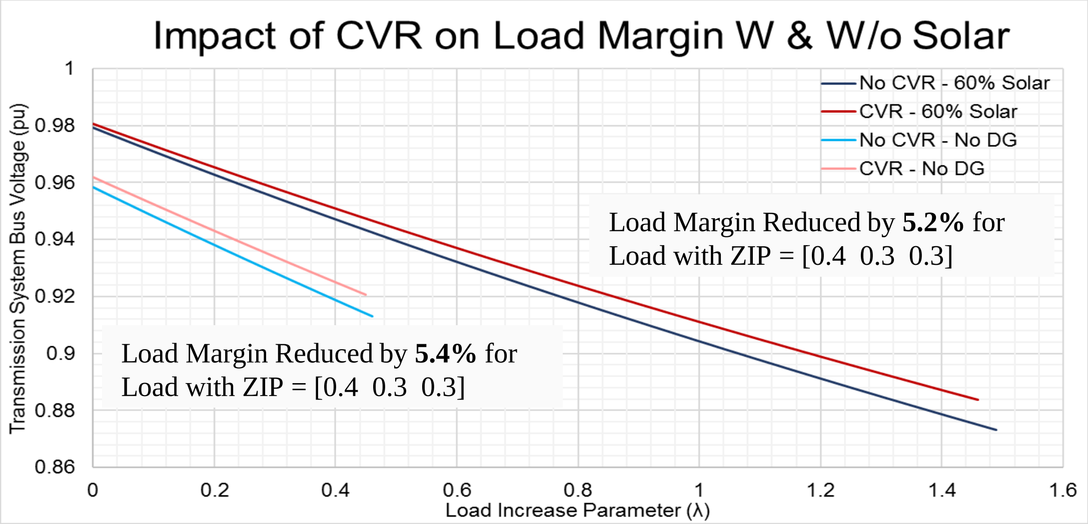
- **9-bus Transmission + 4-bus Distribution**



ZIP Profile	% Reduction in Margin
ZIP= [0.8 0.1 0.1] Z	2.69 %
ZIP= [0.1 0.8 0.1] I	8.11 %
ZIP= [0.1 0.1 0.8] P	13.23%

From a planning perspective, the type of load increasing on the distribution system needs to be monitored to understand the impact of CVR on the system load margin

- **9-bus Transmission + 34-bus Distribution**

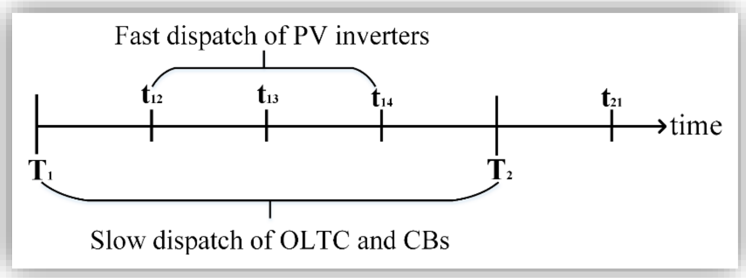


- CVR reduces the system long-term load margin
- Presence of DG does not effect CVR impact on load margin significantly

CVR reduces the long-term load margin of the System with or without DG

Distributed CVR in Unbalanced Distribution Systems with PV Penetration

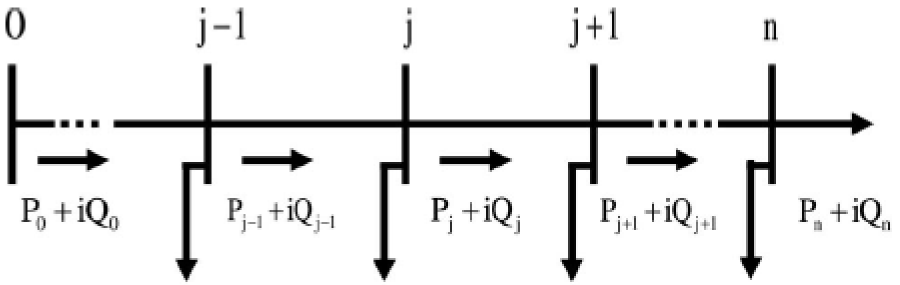
In this paper, a distributed multi-objective optimization model is proposed to coordinate the fast-dispatch of photovoltaic (PV) inverters with the slow-dispatch of on-load tap changer (OLTC) and capacitor banks (CBs) for implementing CVR in unbalanced three-phase distribution systems.



- An optimization model is developed to coordinate the fast dispatch of PV inverters with the slow-dispatch of OLTC and CBs, in order to facilitate voltage reduction in unbalanced three-phase distribution systems.
- In order to ensure the solution optimality and maintain customer data privacy, a distributed solution methodology is proposed to dispatch all the abovementioned devices in a unified optimization framework. The solution methodology is based on a modified ADMM technique to handle the non-convexity introduced by discrete switching and tap changing variables.
- The trade-off between voltage reduction and real power loss reduction is quantified numerically using the developed multi-objective VVO formulation.

Dist-Flow Method

The distribution power flow (Dist-Flow) method has been widely applied to distribution networks with a high accuracy and computational efficiency compared to other load flow algorithms.



$p_j + iq_j$ $p_{j+1} + iq_{j+1}$

- $p_{j+1}^{(c)}, q_{j+1}^{(c)}$: Consumption of power at Bus j+1
- $p_{j+1}^{(g)}, q_{j+1}^{(g)}$: Generation of power at Bus j+1
- r_j, x_j: Complex impedance of the line between Bus *j* to Bus *j+1*
- $\mathrm{r_j}\frac{\mathrm{P_j^2+Q_j^2}}{\mathrm{V_j^2}}, \mathrm{x_j}\frac{\mathrm{P_j^2+Q_j^2}}{\mathrm{V_j^2}}$: Active and reactive power losses on line between Bus *j* to Bus *j+1*

- Active (P_{j+1}) and Reactive (Q_{j+1}) Branch Power Flow from Bus *j* to Bus *j+1*:

$$P_{j+1} = P_j - p_{j+1} - \mathrm{r_j}\frac{\mathrm{P_j^2 + Q_j^2}}{\mathrm{V_j^2}}$$

$$Q_{j+1} = Q_j - q_{j+1} - \mathrm{x_j}\frac{\mathrm{P_j^2 + Q_j^2}}{\mathrm{V_j^2}}$$

- Nodal Voltage (V_{j+1}) on Bus *j+1*:

$$V_{j+1}^2 = V_j^2 - 2\left(r_j P_j + x_j Q_j\right) + \left(\mathrm{r_j^2} + \mathrm{x_j^2}\right)\frac{\mathrm{P_j^2+Q_j^2}}{\mathrm{V_j^2}}$$

- Extracted Active (p_{j+1}) and Reactive (q_{j+1}) Power on Bus *j+1*:

$$p_{j+1} = p_{j+1}^{(c)} - p_{j+1}^{(g)}$$

$$q_{j+1} = q_{j+1}^{(c)} - q_{j+1}^{(g)}$$

Linearized Dist-Flow Method

However, the branch power flow and voltage constraints in Dist-Flow method have nonlinear power loss terms ($\frac{P_i^2+Q_i^2}{V_i^2}$) that make the problem non-convex.

Neglect the nonlinear terms: In some previous works, the linearization is based on the fact that the nonlinear terms are much smaller than the linear terms. So the nonlinear terms are neglected for the sake of developing efficient solution algorithms.

$$P_{j+1} = P_j - p_{j+1} - r_j \frac{P_j^2 + Q_j^2}{V_j^2} \quad \Rightarrow \quad P_{j+1} = P_j - p_{j+1}$$

$$Q_{j+1} = Q_j - q_{j+1} - x_j \frac{P_j^2 + Q_j^2}{V_j^2} \quad \Rightarrow \quad Q_{j+1} = Q_j - q_{j+1}$$

$$V_{j+1}^2 = V_j^2 - 2\left(r_j P_j + x_j Q_j\right) + \left(r_j^2 + x_j^2\right) \frac{P_j^2+Q_j^2}{V_j^2} \quad \Rightarrow \quad V_{j+1}^2 = V_j^2 - 2\left(r_j P_j + x_j Q_j\right)$$

Extension to Unbalanced Three-Phase Systems

In a single-phase distribution system, it has

$$V_k = V_i - z_{ik}\frac{P_{ik} - jQ_{ik}}{V_i^*}$$

To extend it to three-phase

$$V_k = V_i - z_{ik}[(P_{ik} - jQ_{ik}) \oslash V_i^*]$$

Where $V_i = [V_{i_a}, V_{i_b}, V_{i_c}]^T, V_k = [V_{k_a}, V_{k_b}, V_{k_c}]^T$, $P_{ik} = [V_{ik_a}, V_{ik_b}, V_{ik_c}]^T$, $Q_{ik} = [Q_{ik_a}, V_{ik_b}, V_{ik_c}]^T$, $z_{ik} \in \mathbb{C}^{3\times 3}$ $\oslash$ and $\odot$ denote the element-wise division multiplication, respectively.

- Unlike the per-phase equivalent case, multiplying by the complex conjugate of both sides of the three-phase formulation will not remove the dependence on θ. This is due to the fact that there is a coupling between the phase at bus *i* that arises from the cross-products of the three-phase equations for the phase voltage and line current.
- To address this problem, it has observed that the voltage magnitude between the phases are similar, i.e., $|V_{i_a}| \approx |V_{i_b}| \approx |V_{i_c}|$, and that the phase unbalances on each bus are not very severe, so it assumes that the voltages are nearly balanced. Thus, it can approximate the phase different at bus *i* as:

$$\cos(\theta_{i_a} - \theta_{i_a}) = \cos\left(\frac{2}{3}\pi + \boldsymbol{\alpha}\right) = -\frac{1}{2}\cos(\boldsymbol{\alpha}) - \frac{\sqrt{3}}{2}\sin(\boldsymbol{\alpha}) \approx -\frac{1}{2}$$

$$\sin(\theta_{i_a} - \theta_{i_b}) = \sin\left(\frac{2}{3}\pi + \boldsymbol{\alpha}\right) = \frac{1}{2}\cos(\boldsymbol{\alpha}) + \frac{\sqrt{3}}{2}\sin(\boldsymbol{\alpha}) \approx \frac{\sqrt{3}}{2}$$

Where $\boldsymbol{\alpha}$ represents the relative phase unbalance, which is sufficiently small and can be neglected.

Multi-objective Optimization Model

A centralized optimization model is presented to coordinate the fast-dispatch of PV inverters and the slow-dispatch of conventional voltage regulation devices (OLTC and CBs) to facilitate voltage reduction in unbalanced distribution systems.

$$\min_{V_i,P_i,Q_i}\left(w_1\sum_{i=1}^{N}\left(V_{i,\phi}^{*}\right)+w_2\sum_{i=1}^{N}\left(loss_{i,\phi}\right)\right)$$

Multi-objective function aims to (1) minimize the largest bus voltage; (2) minimize active power losses, with the weight factors w_1 and w_2. The distribution system operators can adjust the weighting factors w1 and w2 according to specific operational requirements.

s.t.

$$V_{i,\phi}^{*}\geq\max_{t\in T}\left(V_{i,t,\phi}\right)$$

Find the largest voltage magnitude at bus *i* at time t.

$$loss_{i,\phi}=\sum_{t=1}^{T}\left(r_{i,\phi}\frac{\left(P_{i,t,\phi}^{l}\right)^2+\left(Q_{i,t,\phi}^{l}\right)^2}{V_s^2}\right)$$

Determine the overall active power losses on the line connecting bus *i* and bus *i-1* at t.

Multi-objective Optimization Model

$$P_{i,t,\phi}^{l} = P_{i-1,t,\phi}^{l} - P_{i,t,\phi}^{ZIP} + P_{i,t,\phi}^{pred}$$

Nodal active power balance formulation, which includes the active power in-flow and out-flow at bus *i*, active power output of PV inverter, as well as the ZIP active load of bus *i*.

$$P_{i,t,\phi}^{PV} = P_{i,t,\phi}^{pred} - \varepsilon_{i,t,\phi}$$

The uncertainty of PV power is represented by Gaussian random variables for PV power prediction error. Accordingly, each agent predicts the available nodal PV power over the decision window. Due to the uncertainty of PV power in real-time, the predicted value $P_{i,t,\phi}^{pred}$ is different from the actual PV power $P_{i,t,\phi}^{PV}$. The difference is modeled using a Gaussian error variable $\varepsilon_{i,t,\phi}$.

$$Q_{i,t,\phi}^{l} = Q_{i-1,t,\phi}^{l} - Q_{i,t,\phi}^{ZIP} + Q_{i,t,\phi}^{PV} + Q_{i,t}^{CB}$$

Nodal reactive power balance formulation, which determines the reactive power output of PV inverter at bus *i* and reactive power output of CB at bus *i*.

$$-q_{i,t,\phi}^{*} \le Q_{i,t,\phi}^{PV} \le q_{i,t,\phi}^{*}$$

$$q_{i,t,\phi}^{*} = \sqrt{\left(S_{i,t,\phi}^{PV}\right)^2 - \left(P_{i,t,\phi}^{pred}\right)^2}$$

Limit the reactive power capacity of PV inverters based on PV generation capacity and the active power output.

$$Q_{i,t,\phi}^{CB} = I_{i,t}^{CB} q_i^{CB}$$

Obtains the CB reactive power injection at bus *i*. $I_{i,t}^{CB}$ represents the on/off status of the CB at bus *i* during the dispatch period *T*. For buses without CB, q_i^{CB} is set to zero.

Multi-objective Optimization Model

$$P_{i,t,\phi}^{ZIP} = P_{i,t,\phi}^{D}(Z_i^p V_{i,t,\phi}^2 + I_i^p V_{i,t,\phi} + P_i^p)$$

$$Q_{i,t,\phi}^{ZIP} = Q_{i,t,\phi}^{D}(Z_i^q V_{i,t,\phi}^2 + I_i^q V_{i,t,\phi} + P_i^q)$$

The ZIP active and reactive load by second-order polynomial formulations. Summation of ZIP coefficients for both active and reactive are set to 1. $P_{i,t,\phi}^{D}$ and $Q_{i,t,\phi}^{D}$ are active and reactive power demand factors during the dispatch period, respectively.

$$V_{i,t,\phi} = V_{i,t,\phi} - \frac{r_{i-1,t,\phi} P_{i-1,t,\phi}^{l} + x_{i-1,t,\phi} Q_{i-1,t,\phi}^{l}}{V_s}$$

Bus voltage using DistFlow equations

$$V_{1,t} = V_s + I_t^{tap} V^{tap}$$

The substation transformer secondary voltage $V_{1,t}$ according to primary voltage V_s and OLTC tap position I_t^{tap}.

$$V_{i,t}^{min} \le V_{i,t,\phi} \le V_{i,t}^{max}$$

The bus voltage is maintained within the allowable range, and the voltage limits are set to be [0.95, 1.05].

$$\sum_{t \in T} \left| I_{i,t}^{CB} - I_{i-1,t}^{CB} \right| \le CB^{max}, I_{i,t}^{CB} \in \{0,1\}$$

$$\sum_{t \in T} \left| I_t^{tap} - I_{t-1}^{tap} \right| \le TAP^{max}$$

$$I_t^{tap} \in \{-10, -9, \dots, 0, \dots 9, 10\}$$

The maximum allowable switching actions of CBs and OLTC during the dispatch period. For example, in the following case studies, the CB^{max} is set to be 3 and TAP^{max} is set to be 5.

Modified ADMM

- In the optimization model, there are discrete variables: CB switching status and OLTC tap positions.
- The alternating direction method of multipliers (ADMM) is originally developed to solve convex problem in a distributed manner, hence, modifications to ADMM are necessary to approporiately and efficiently handle the discrete variables.
- In the proposed method, discrete variables are not only relaxed by continues variables, but also guaranteed as a generalized part of the objective function in the iterative process of ADMM.

(1) MILP

$$\min_{x,I} f(x,I)$$

s.t.

$$I = y$$

$$z = g(x,y)$$

$$I \in \mathbb{Z}, x, y \in \mathbb{R}$$

- Discrete variable I is replaced with an auxiliary continuous variable y.
- An additional auxiliary equality is introduced.

(2) Augmented Lagrangian function

$$\mathcal{L}_p = f(x_i, y_i) + \lambda_i^z(z_i - g(x_i, I_i)) + \frac{\rho}{2}\|z_i - g(x_i, I_i)\|_2^2$$

(3) Iterative update rules (with the iteration number denoted by k)

$$(x_i(k+1), y_i(k+1)) = arg\min_{x,y} \mathcal{L}_p$$

$$I_i(k+1) = arg\min_{I}\|z_i(k+1) - g(x_i(k+1), I_i)\|_2^2$$

$$\lambda_i^z(k+1) = \lambda_i^z(k) + \rho(z_i(k+1) - g(x_i(k+1), I_i(k+1)))$$

Iterative Process of ADMM

Decompose the centralized optimal problem to local bus-level optimal problems

In the iterative process of ADMM:

- **Step.1** For each bus agent i at iteration k, local bus-level optimal problem is solved independently (in parallel way).
- **Step.2** For each bus agent i at iteration k, local optimization solution exchanges take place between neighboring agents to update variables based on respective bus local variables and variables at buses connected to bus i, which are obtained from Step 1.
- **Step.3** For each bus i at iteration k, the Lagrange multipliers are updated based on the ADMM iterative rules and the variables obtained in previous steps. Hence, the Lagrange multipliers for variable set x_i are updated.
- **Step.4** Increase iteration k by 1 till it reaches the maximum iteration number.

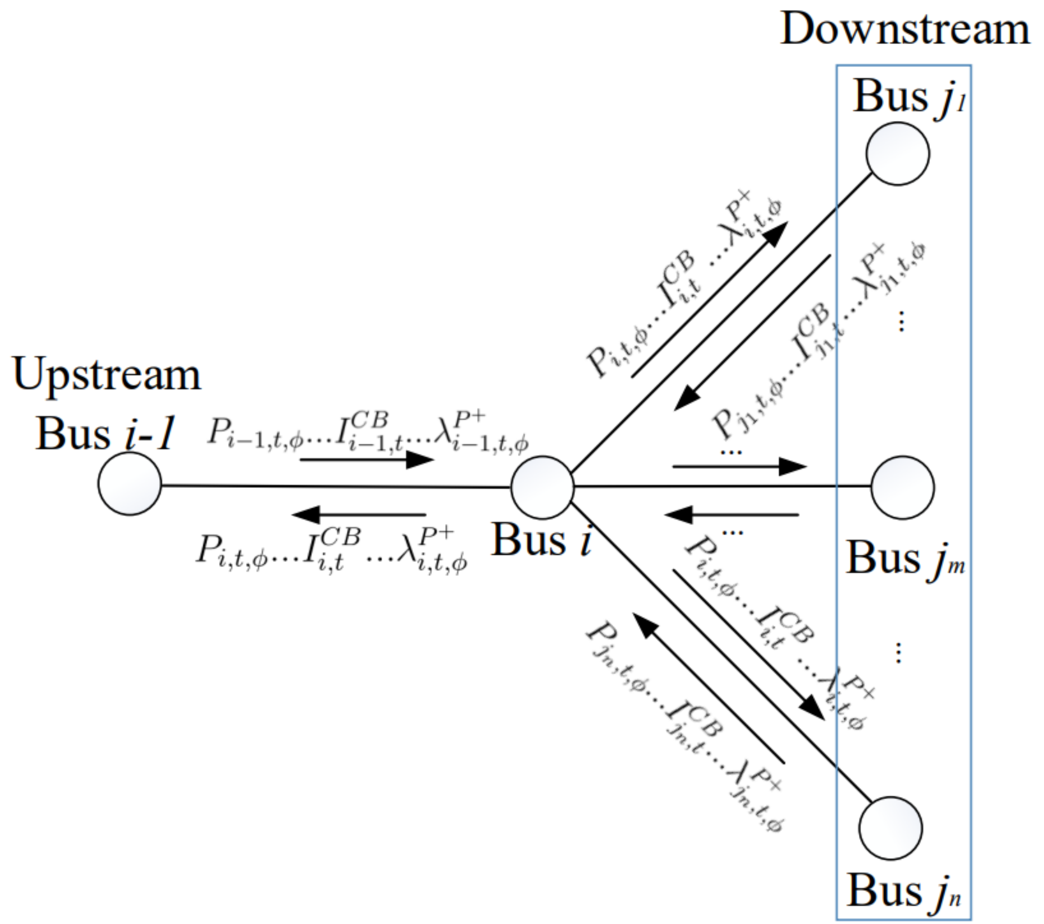


Fig. 3. Local optimization solution exchange between control agents at different buses

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Algorithm Convergence: IEEE 13-bus System

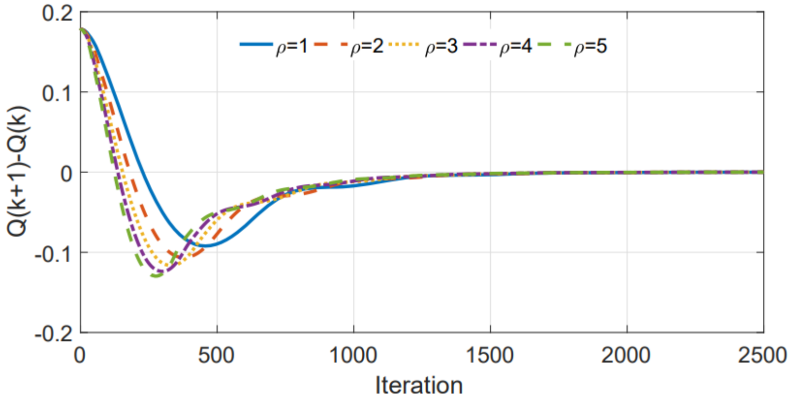

Fig. 4. Convergence of the distributed optimization: Impact of different penalty parameter ρ values

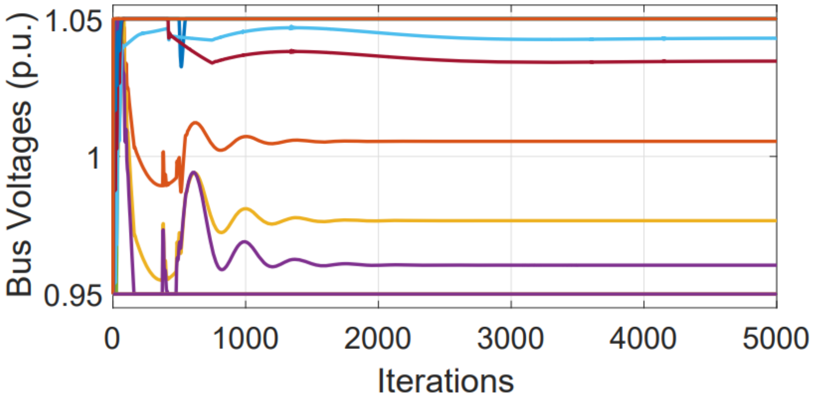

Fig. 5. Convergence of the distributed optimization: Iterative updates of bus voltage magnitudes ρ=5

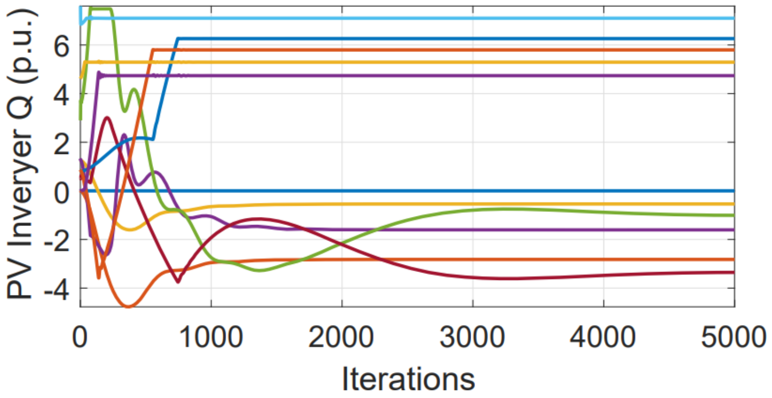

Fig. 6. Convergence of the distributed optimization: Iterative updates of PV inverter reactive power outputs ρ=5

- Fig. 4 shows the convergence results for different values of ρ. Within certain range of ρ, the proposed algorithm can converge faster with larger values. However, increasing to a too large value will cause numerical instability and divergence.

- Based on Fig. 5 and Fig. 6, it can be seen that most of variables converge after 3000 iterations, while only a few take more than 4000 iterations to converge.

Numerical Results: IEEE 34-bus System

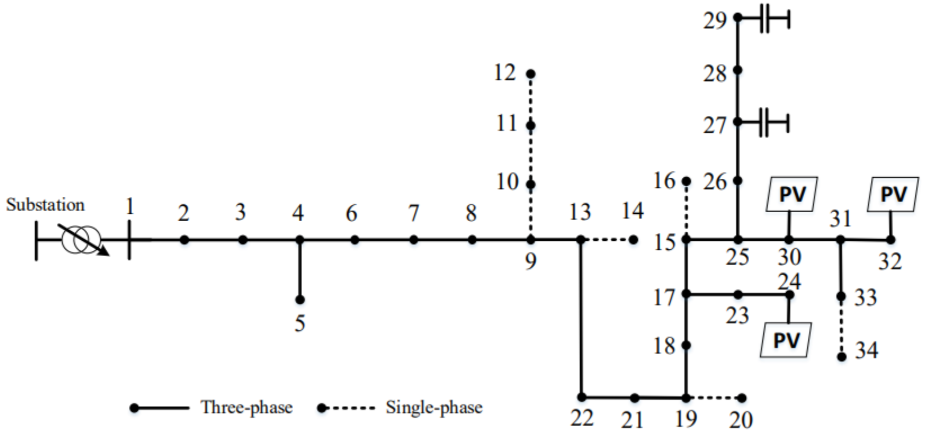

Fig. 7. Case II: Modified IEEE 34-bus test distribution system

TABLE I
ZIP COEFFICIENTS FOR EACH CUSTOMER TYPE [28]

Bus Type	Zp	Ip	Pp	Zq	Iq	Pq
Commercial	0.43	-0.06	0.63	4.06	-6.65	4.49
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77
Industrial	0	0	1	0	0	1

TABLE II
CASE II: BUS TYPE

Type	Residential	Commercial	Industrial
Bus number	2,3,4,5,9,10, 11,12,13,14,16, 17,18,19,20,22, 24,26,28,33,34	15,21, 25,30,31	27,29, 32

** Different weight factors: Opt.1, Opt.2, Opt.3, Opt.4 and Opt.5, (w_1, w_2) change from $(1,0)$ to $(0,1)$*

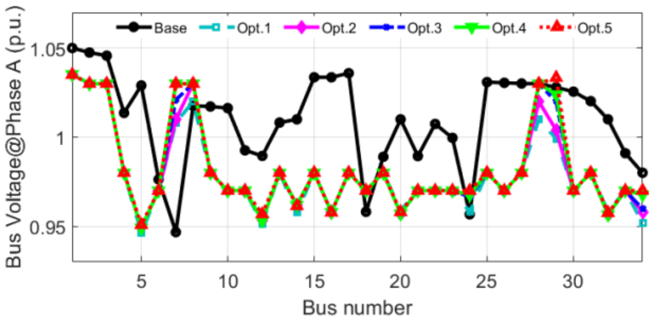

Fig. 9. Case II: Voltage profiles at t=1 and for ϕ_A of base case and cases *Opt. 1* to *Opt. 5*

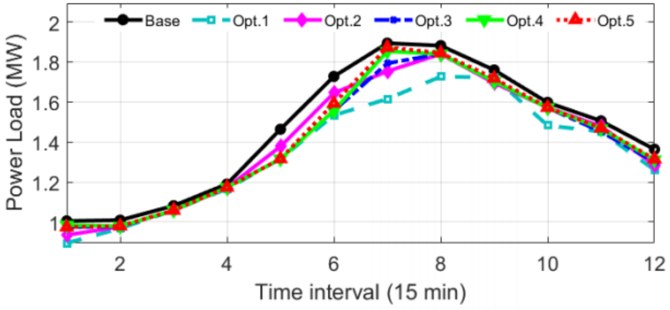

Fig. 10. Case II: Load power consumption for the base case and cases *Opt. 1* to *Opt. 5*

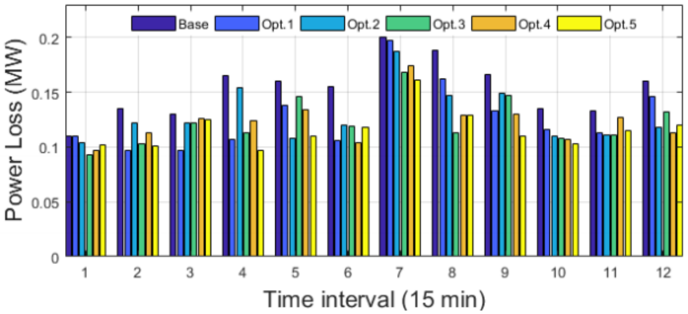

Fig. 11. Case II: Power losses for the base case and cases *Opt. 1* to *Opt. 5*

- Fig. 9 shows voltage profiles of a for all cases, including the base case, in one snapshot. The optimal voltage magnitudes of Opt. 1 to Opt. 5 are generally lower than the base case (black solid line), which shows the voltage reduction effects of VVO.

- Fig. 10 and Fig. 11 present the load power consumption and power losses of the base case and CVR cases Opt.1 to Opt.5, respectively.

- Among the cases Opt.1 to Opt.5 and the base case, Opt.1 has the largest load reduction and Opt.5 has the largest loss reduction, which shows the effect of various w1 and w2, respectively.

- Hence, it is corroborated that by changing the weight factors in the optimization model the trade-off between CVR and loss minimization in the final decision solution can be controlled effectively.

Numerical Results: IEEE 123-bus System

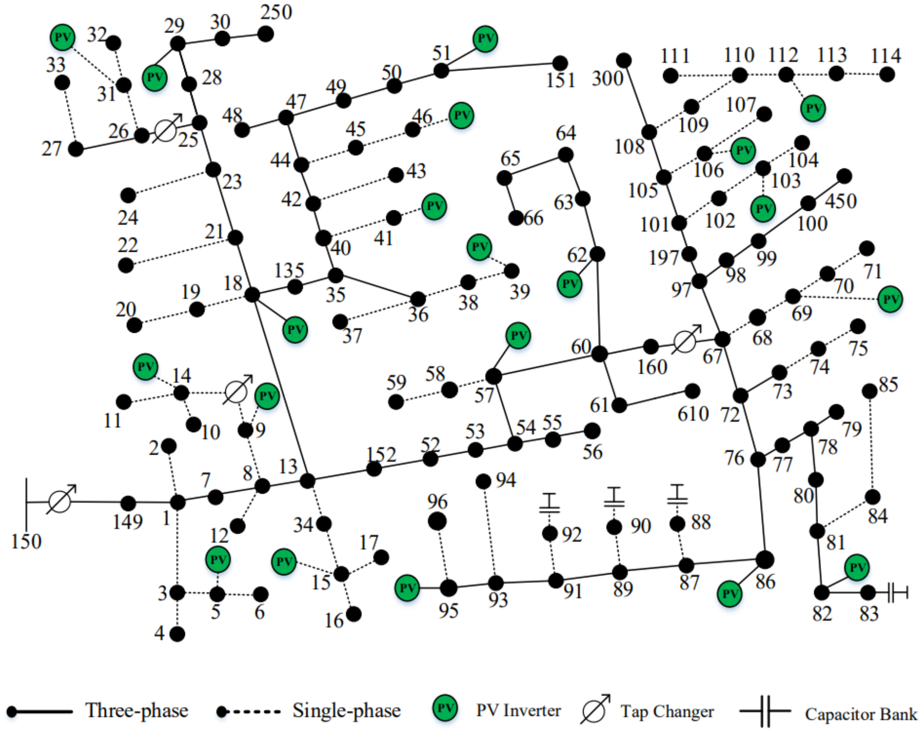

Fig. 13. Case III: Modified IEEE 123-bus test distribution system

** Different ZIP factors: ZIP1, ZIP2 and ZIP3*
** Different weight factors: Opt.1, Opt.2, Opt.3, Opt.4 and Opt.5*

TABLE VII
CASE III: SUMMARY OF LOSS, LOAD AND TOTAL ENERGY REDUCTION WITH DIFFERENT ZIP FACTORS AND WEIGHT FACTORS

Cases		Loss reduction	Load reduction	Total reduction
ZIP1 (0.4,0.3,0.3)	Opt.1	4.60%	6.32%	6.20%
	Opt.2	6.29%	5.36%	5.42%
	Opt.3	8.53%	4.08%	4.39%
	Opt.4	11.72%	2.98%	3.58%
	Opt.5	14.05%	2.23%	3.04%
ZIP2 (1,0,0)	Opt.1	3.68%	9.68%	9.27%
	Opt.2	5.81%	9.13%	8.91%
	Opt.3	8.19%	8.48%	8.46%
	Opt.4	10.34%	7.41%	7.61%
	Opt.5	12.79%	6.65%	7.07%
ZIP3 (0,0,1)	Opt.1	-6.34%	0.00%	-1.20%
	Opt.2	-5.89%	0.00%	-1.12%
	Opt.3	-5.65%	0.00%	-1.07%
	Opt.4	-1.52%	0.00%	-0.29%
	Opt.5	2.70%	0.00%	0.51%

- For ZIP1 and ZIP2, loss reduction levels are increasing from Opt. 5 to Opt. 1, however, the load reduction and total energy reduction decrease at the same time.
- Since ZIP3 represents pure constant power loads, consumption levels are always the same as the base case regardless of bus voltage levels, and the loss reduction and total energy reduction increase for Opt. 1 to Opt. 5.
- For voltage-dependent loads, ZIP1 and ZIP2, load reduction (due to voltage reduction) accounts for the majority of the change in total energy savings.
- CVR has no impact on the constant power loads, ZIP3, for that case load reduction is zero and the loss optimization is the only effective method to reduce the peak demand.

Overview of Decentralized VVC

Addressing the challenges of

- Limited and varying rates of communication links in current distribution systems
- Time variant operating conditions due to intermittent loads and renewable sources

Dynamic studies for local VVC [TSIPN ‘2017]

- Studied the impact of droop coefficient and level of dynamics on the performance of local VVC mechanisms

Dynamic studies for hybrid VVC [TSG ‘2018]

- Developed a hybrid (consists both distributed and local control designs) VVC scheme that adapts to varying rates of communications and dynamic operating conditions
- Studied the performance with real load and solar profile data

[TSIPN ‘2017] H. J. Liu, W. Shi and H. Zhu, "Decentralized Dynamic Optimization for Power Network Voltage Control," in IEEE Transactions on Signal and Information Processing over Networks, vol. 3, no. 3, pp. 568-579, Sept. 2017.
[TSG ‘2018] H. J. Liu, W. Shi and H. Zhu, "Hybrid Voltage Control in Distribution Networks Under Limited Communication Rates," in *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2416-2427, May 2019.

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Conclusions

- Online load model parameter identification is essential to assess CVR effects
- As the electricity prices and load consumptions are time-varying, it is expected that the proposed CVR effects assessment model could be useful for more detailed cost/benefit analysis
- For dominating fractions of voltage dependent loads, optimizing maximum voltage reduction seems to be better than optimizing losses
- Proposed hybrid design noticeably improves the voltage regulation performance even after the communication links fail
- CVR negatively affects the long-term load margin of the system

Publications

[1] Q. Zhang, K. Dehghanpour and Z. Wang, "Distributed CVR in Unbalanced Distribution Systems with PV Penetration," in *IEEE Transactions on Smart Grid*, accepted for publication.

[2] A. K. Bharati, A. Singhal, V. Ajjarapu and Z. Wang, "Comparison of CVR impact on transmission system load margin with aggregated and de-aggregated distribution system," *2017 North American Power Symposium (NAPS)*, Morgantown, WV, 2017, pp. 1-6.

[3] A. K. Bharati, A. Singhal, V. Ajjarapu and Z. Wang, "Analysis of CVR Impact on Voltage Stability Margin using T&D Co-Simulation,“, under review on *IET Generataion, Transmission and Distribution Special issue: Unlocking the full Benefits of TSO-DSO Interaction*, 2019.

[4] J. Zhao, Z. Wang and J. Wang, "Robust Time-Varying Load Modeling for Conservation Voltage Reduction Assessment," in *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3304-3312, July 2018.

[5] H. J. Liu, W. Shi and H. Zhu, "Hybrid Voltage Control in Distribution Networks Under Limited Communication Rates," in *IEEE Transactions on Smart Grid*, vol. 10, no. 3, pp. 2416-2427, May 2019.

[6] H. J. Liu, W. Shi and H. Zhu, "Decentralized Dynamic Optimization for Power Network Voltage Control," in *IEEE Transactions on Signal and Information Processing over Networks*, vol. 3, no. 3, pp. 568-579, Sept. 2017.

Thank You!
Q & A

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