

NC STATE
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FREEDM
SYSTEMS CENTER

Annual Research
Symposium 2026

**Flexible Scheduling of Large EV loads for Improving
Power Distribution Grid Stability**



**Dominion
Energy®**

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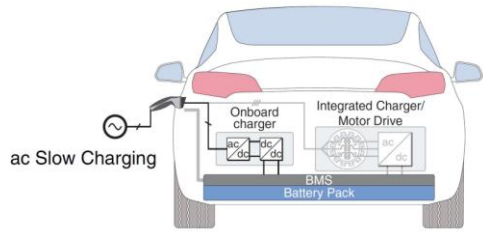
Category of EV Chargers

Level 1

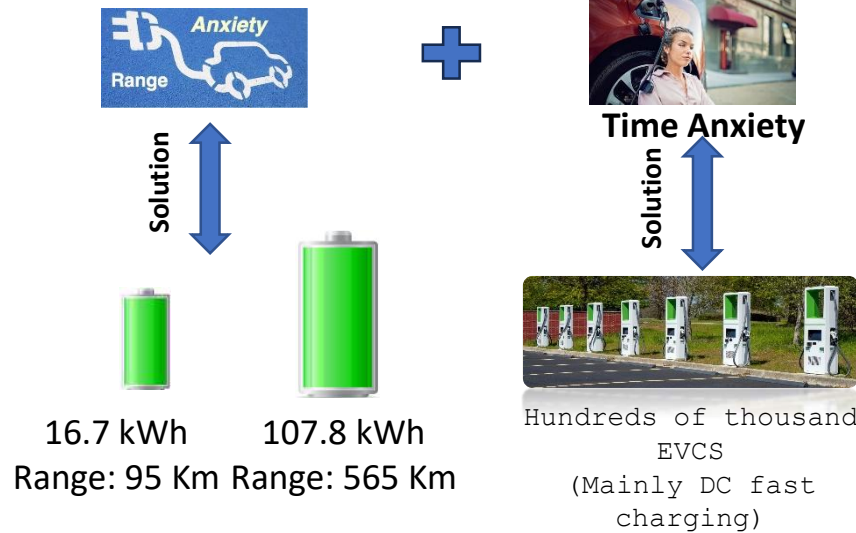
1.44-1.9 kW charging rate
Charging time: 20 h for 200 km

Level 2

3.1-19.2 kW charging rate
Charging time: 5 h for 200 km

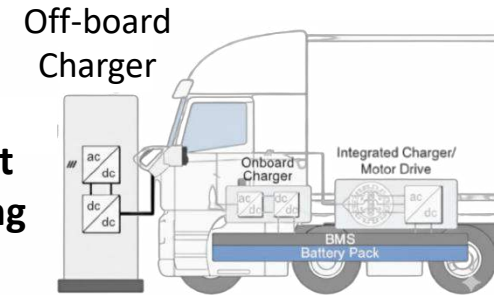


EV growth concerns and solution



Level 3

20-350 kW charging rate
Charging time: ±30 min for 80% of 200 km

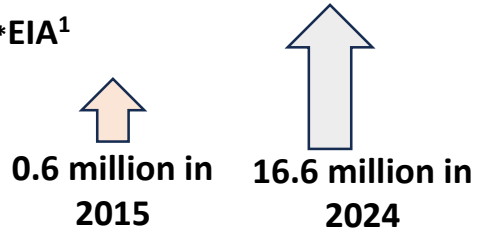


DC Fast Charging

Heavy-duty electric trucks and buses

Worldwide EV growth

*EIA¹



Worldwide Growth of DCFC

*EIA¹

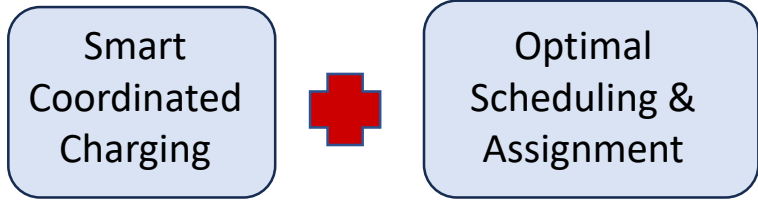


Is our legacy grid robust enough to handle the high penetration of DC fast charging load ?

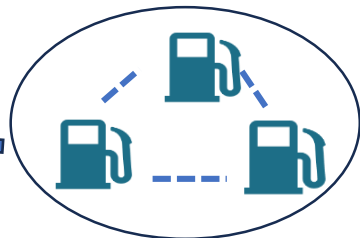
EV= Electric Vehicle, EVCS= Electric Vehicle Charging Stations, DCFC=Direct Current Fast chargers

[1] <https://www.iea.org/data-and-statistics/charts/global-electric-car-sales-and-cop28-pathway-2030>

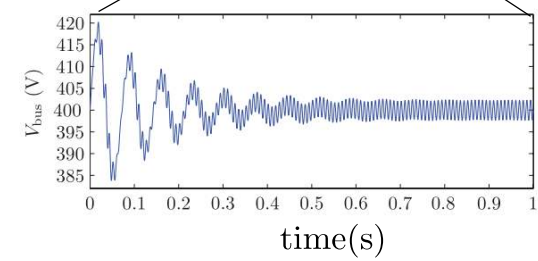
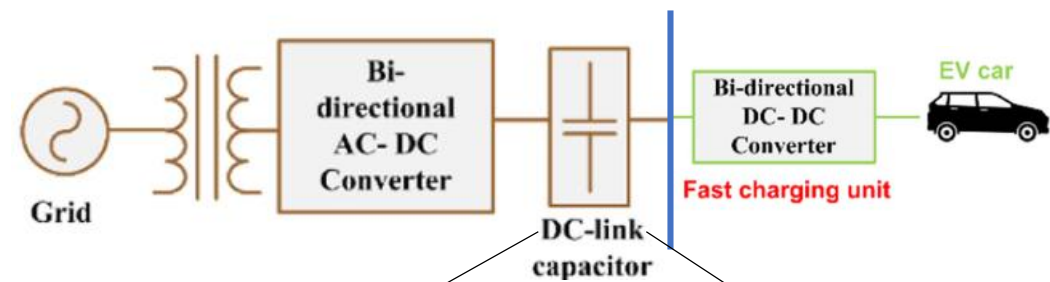
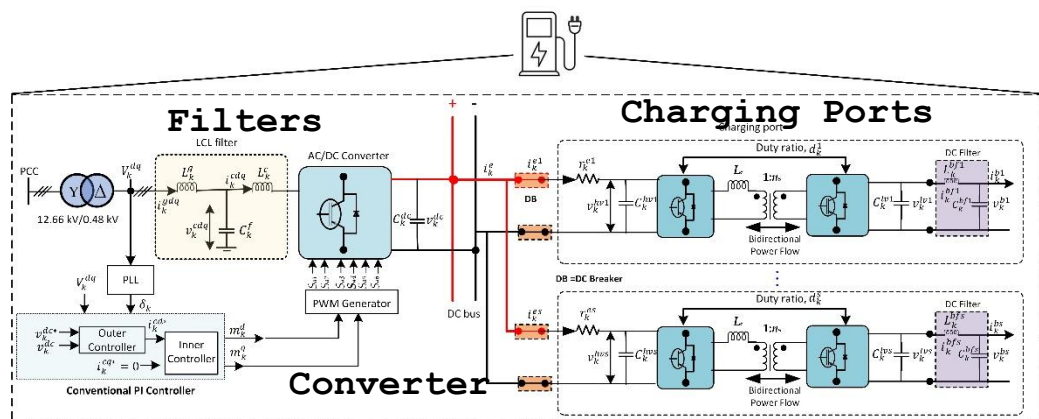
In tackling EV charging issues, the most studied solutions are



Aggregated static representation of EV load in optimization problem



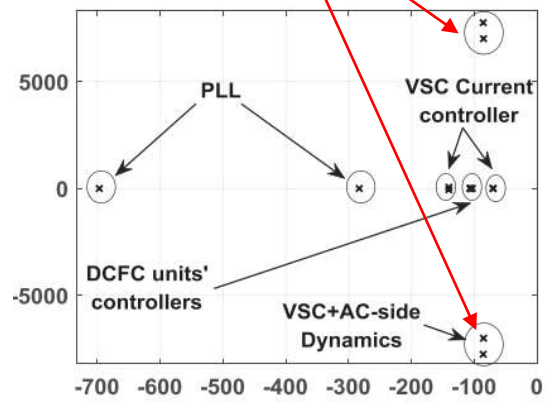
Constant power load



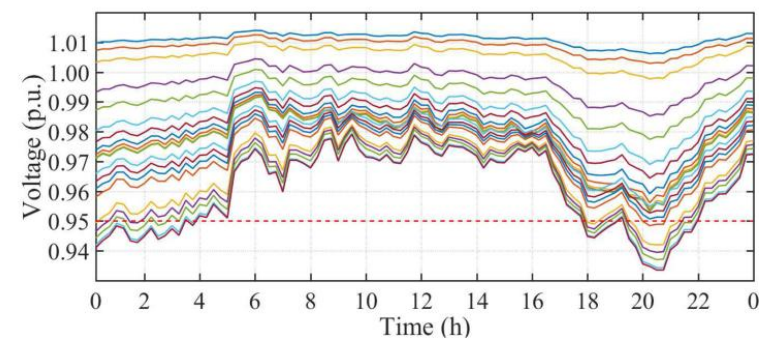
DC bus voltage fluctuation issues due to sudden plug-in and out of high-power EV load [2]

Open-loop Eigenvalue Analysis

High frequency oscillatory modes [3]

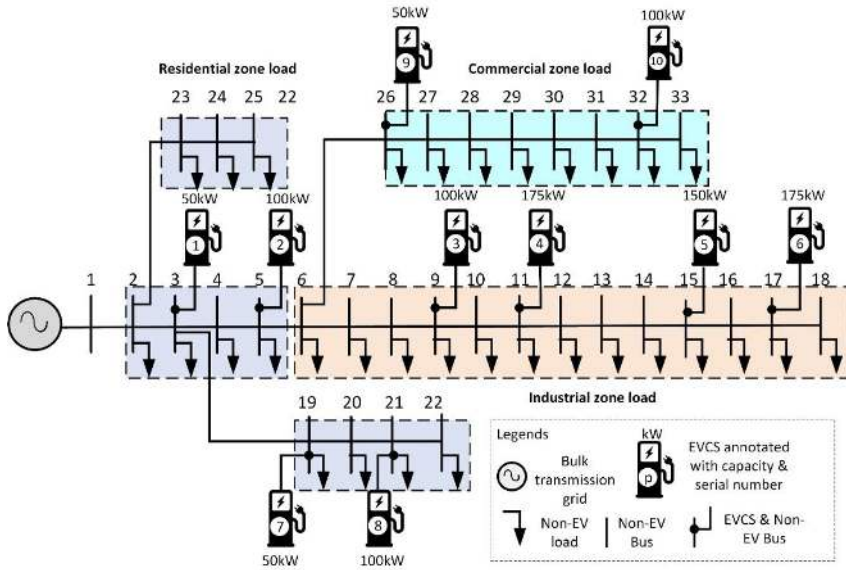


Bus voltage deviations due to EV load [2]



[2] M. Karimi-Ghartemani, S. A. Khajehodini, P. Jain and A. Bakhshai, "A Systematic Approach to DC-Bus Control Design in Single-Phase Grid-Connected Renewable Converters," in *IEEE Transactions on Power Electronics*, vol. 28, no. 7, pp. 3158-3166, July 2013.
 [3] M. M. Mahfouz and M. R. Iravani, "Grid-integration of battery-enabled dc fast charging station for electric vehicles," *IEEE Transactions on Energy Conversion*, vol. 35, no. 1, pp. 375-385, 2020

Modified IEEE 33-bus distribution grid with $p = 10$ EVCSs



Assumptions

- Balanced three-phase circuits with identical passive elements in all three phases
- Lossless power converter during modeling of p EVCSs
- Similar dynamic modeling for all p EVCSs, however, has different values for different ratings.

Notations

\mathbb{N}_P → Index set of point of common coupling buses

\mathbb{N}_E → Index set of EVCS buses

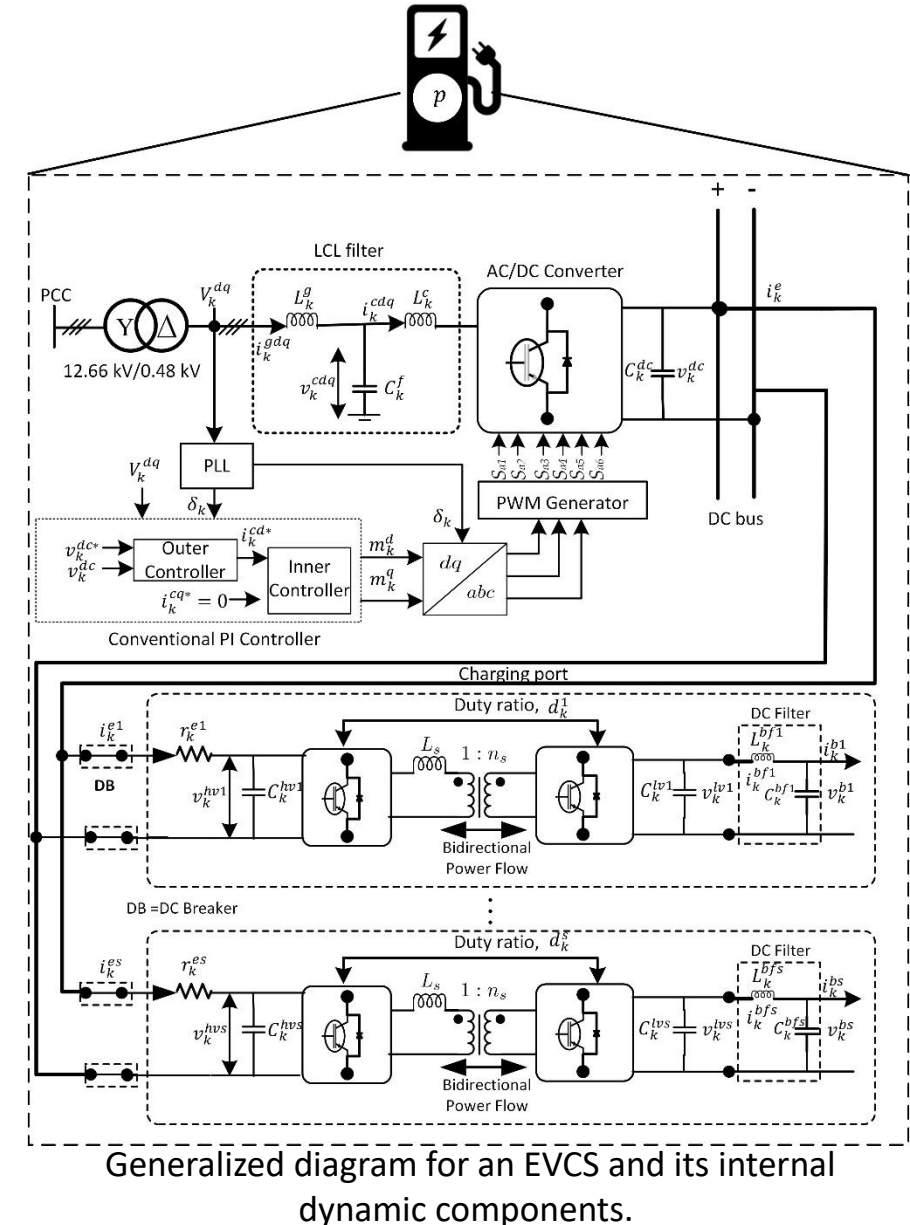
\mathbb{N}_L → Index set of non-EV load buses

$\{P_k^L, Q_k^L\}$ → Constant active and reactive power of non-EV load at $k \in \mathbb{N}_L$ bus

p → Number of EVCSs

n → Number of buses

\mathcal{N}_k → Index set of neighboring bus to the k^{th} bus



The overall state-space model of the EVCS-integrated power system can be presented in a compact form by the following differential-algebraic equations (DAEs):

$$\Sigma_{\text{detail}} : \begin{cases} \dot{x} = f(x, y, u, \alpha) \\ 0 = g(x, y, \alpha) \end{cases}$$

Where,

$$x := \left[\left[\left[\left(x_k^e \right)^T \right]_{k \in \mathbb{N}_E} \right]^T, \left[\left[i_{ka}^d, i_{ka}^q \right]^T_{k \in \{1, \dots, n-1\}, a \in \mathcal{N}_k} \right]^T \right]^T \in \mathbb{R}^{(12+4s)p+2(n-1)}$$

EVCS
Line dynamics

$$x_k^e := \left[\left[\left[\left(\delta_k, \zeta_k \right)^T \right]^T, \left[\left[i_k^{gd}, i_k^{gq}, i_k^{cd}, i_k^{cq}, v_k^{cd}, v_k^{cq} \right]^T \right]^T, \left[\left[\left(\Psi_k, \chi_k^d, \chi_k^q \right)^T \right]^T, \left[\left(v_k^{dc} \right)^T \right]^T, \left[\left[\left(v_k^{hvC}, v_k^{lvC}, i_k^{bfC}, v_k^{bC} \right)^T \right]^T_{C:=\{1, \dots, s\}} \right]^T \right]^T \right]^T \in \mathbb{R}^{(12+4s)}$$

PLL
LCL filter
Outer & Inner Controller
DC bus
Charging port

$$u := \left[\Delta m_k^d, \Delta m_k^q, \Delta i_k^e \right]_{k \in \mathbb{N}_E}^T \in \mathbb{R}^{3p} \rightarrow \text{Control inputs}$$

$$y := \left[V_k^d, V_k^q \right]_{k \in \{1, \dots, n\}}^T \in \mathbb{R}^{2n} \rightarrow \text{Algebraic variables}$$

$$\alpha := \left[i_k^{e*} \right]_{k \in \mathbb{N}_E}^T \in \mathbb{R}^p, \rightarrow \text{Setpoints}$$

Radial Distribution Network

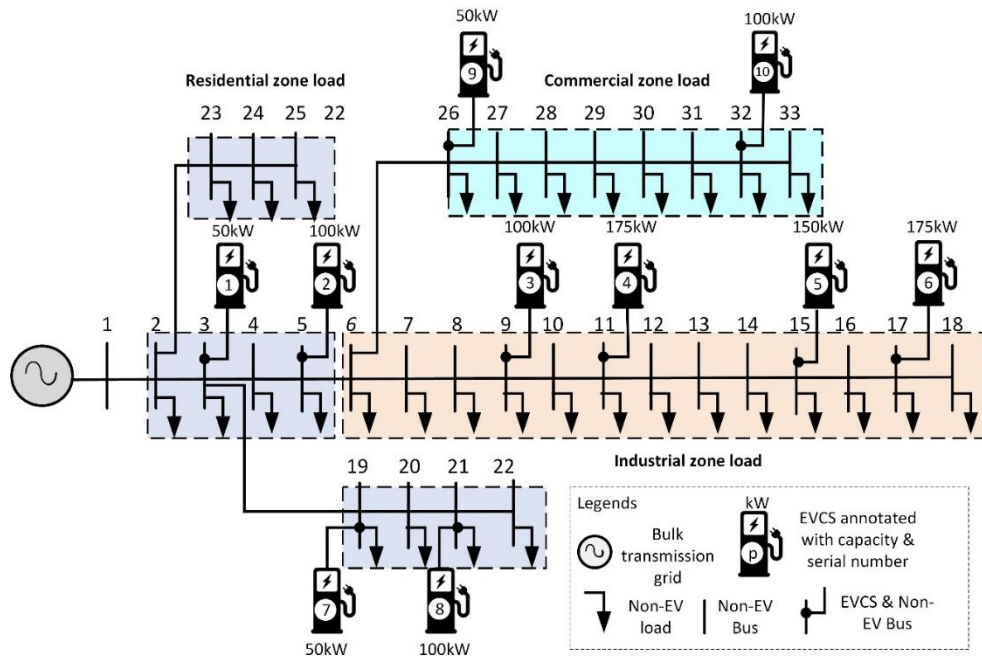


Figure: IEEE 33 bus radial distribution network with 10 EVCSs.

Open-loop Eigenvalue Analysis

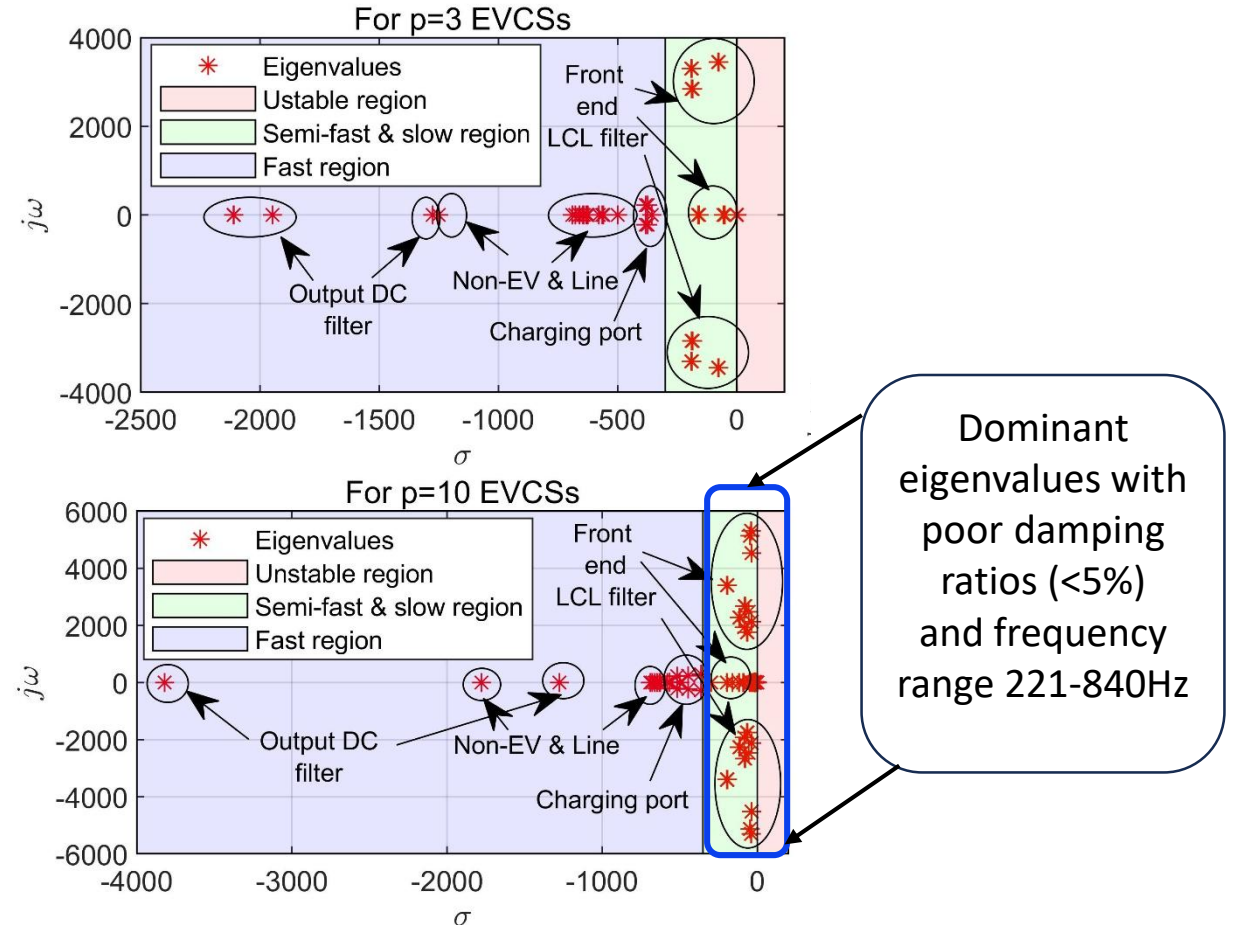
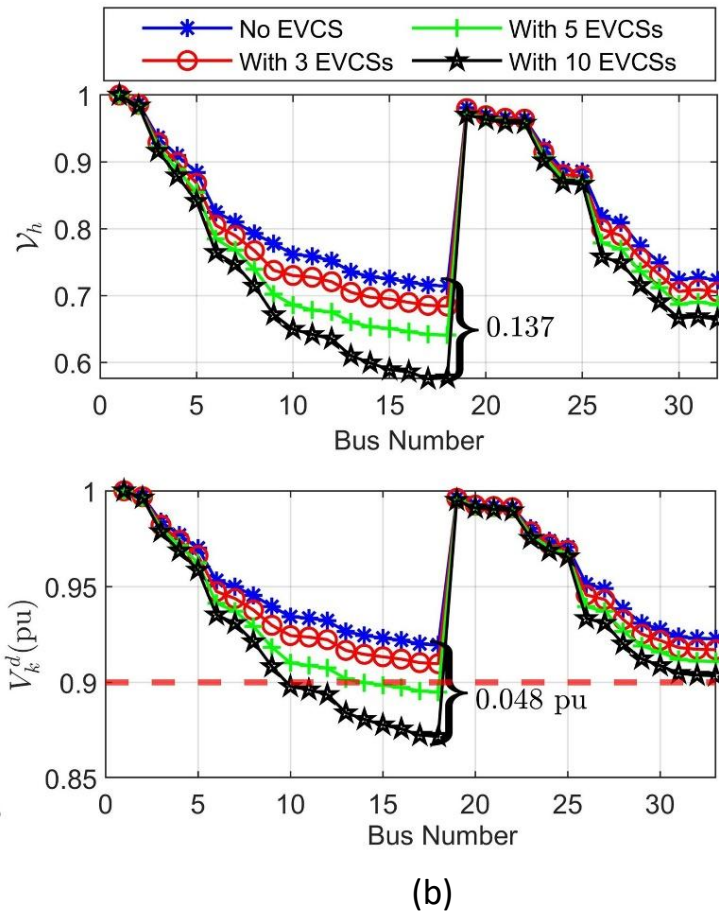
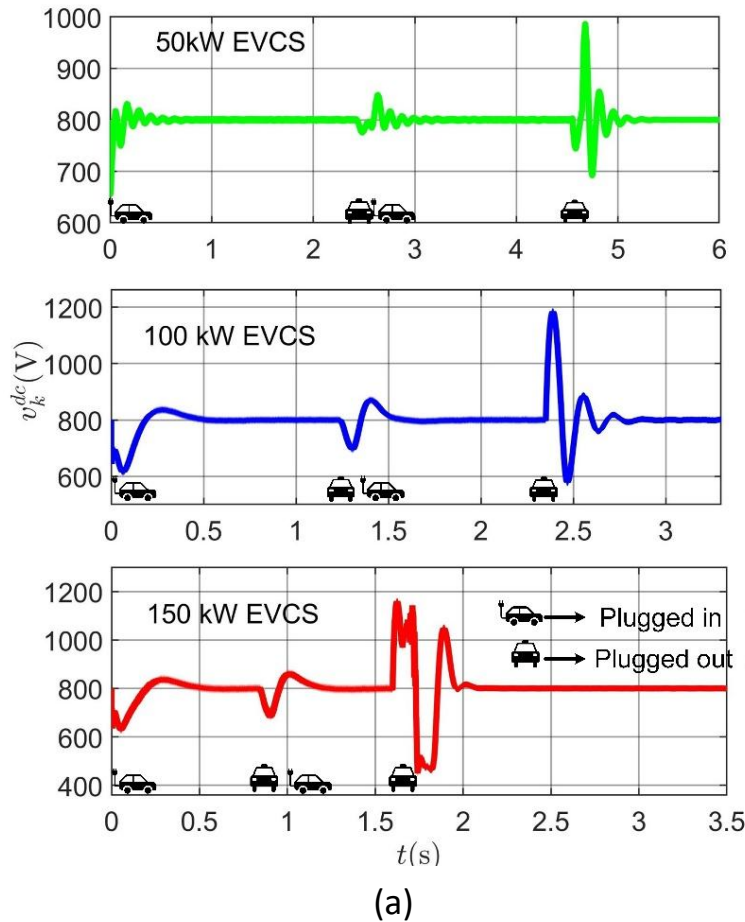


Figure: Open-loop eigenvalues of the linearized 33-bus distribution grid model with 3 and 10 EVCSs.

The voltage suffers from continued **oscillations** that become more severe with the **increase in charging rates and demands**



Voltage stability index (VSI) **decreases** with the increasing power demand, i.e., increasing number of EVCSs.

VSI is a numerical solution, which determines the most sensitive node of a power grid to the voltage collapse. The closer it is to 1, the better it is.

Figure: (a) Transient DC bus voltage inside 1st, 3rd, and 5th EVCSs for p=10 configuration. Note that the charging duration is scaled down from the actual-charging time to highlight the transients in shorter duration. (b) Trends of VSI values of different buses of the network with the increasing number of EVCSs.

Problem 1

Infinite Time Horizon Problem

Optimization Variables

$$J = \min_{K, i^{e*}} (1 - \gamma_1 - \gamma_2) \underbrace{\int_0^\infty \|\hat{z}\|_2^2 dt}_{J_1} + \underbrace{\gamma_1 \|i^{e*} - i^{eD}\|_{2, \beta^{ip}}^2}_{J_2} + \underbrace{\gamma_2 \|\mathbf{1}_n - \mathcal{V}(i^{e*})\|_{\infty, \beta^{si}}}_{J_3}$$

Grid robustness
Incentivization

Voltage stability

s.t: $\dot{\hat{x}} = A(i^{e*})\hat{x} + B(i^{e*})u$ holds

$\hat{z} := Q\hat{x} + Ru, \quad u = -K\hat{x},$

$i_k^{e*} \in [\max\{\underline{i}_k^{e*}, 0\}, i_k^{eD}], \quad k \in \mathbb{N}_{E_{uni}}$

$i_k^{e*} \in [\underline{i}_k^{e*}, i_k^{eD}], \quad k \in \mathbb{N}_{E_{bi}}$

where, $\gamma_1, \gamma_2 \in [0, 1]$ are weighting constants that decide the priorities among small-signal performance, VSI, and incentivization

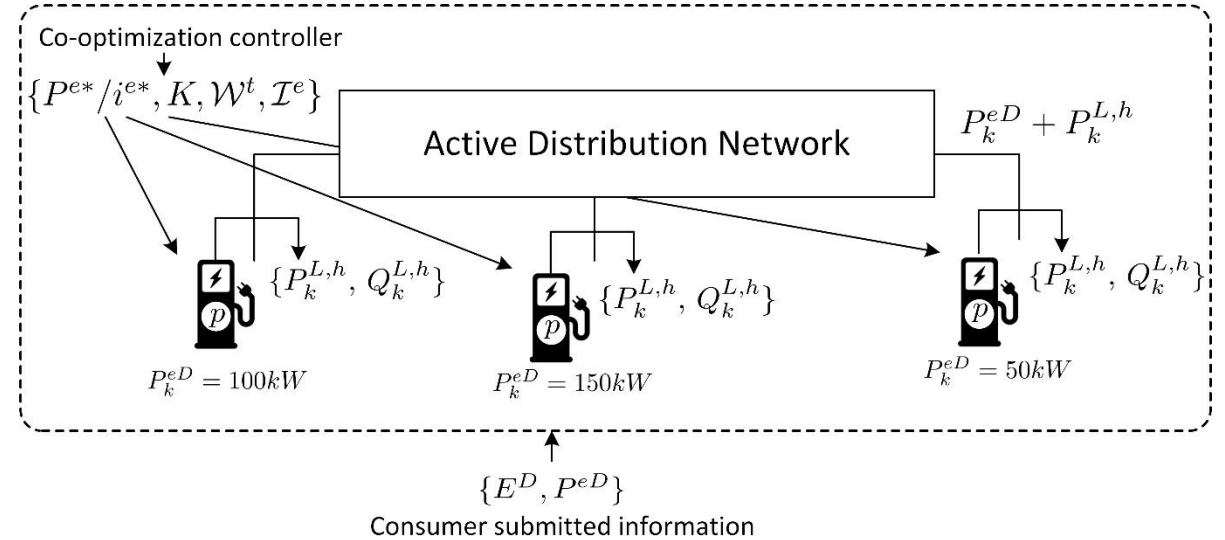


Figure: A conceptual diagram of infinite time horizon problem



Outcome: Optimal charging rate i^{e*} and feedback gain K

Implemented via "Wait & Save" Incentive Strategy

Transient Performance Analysis

Single port EVCSs

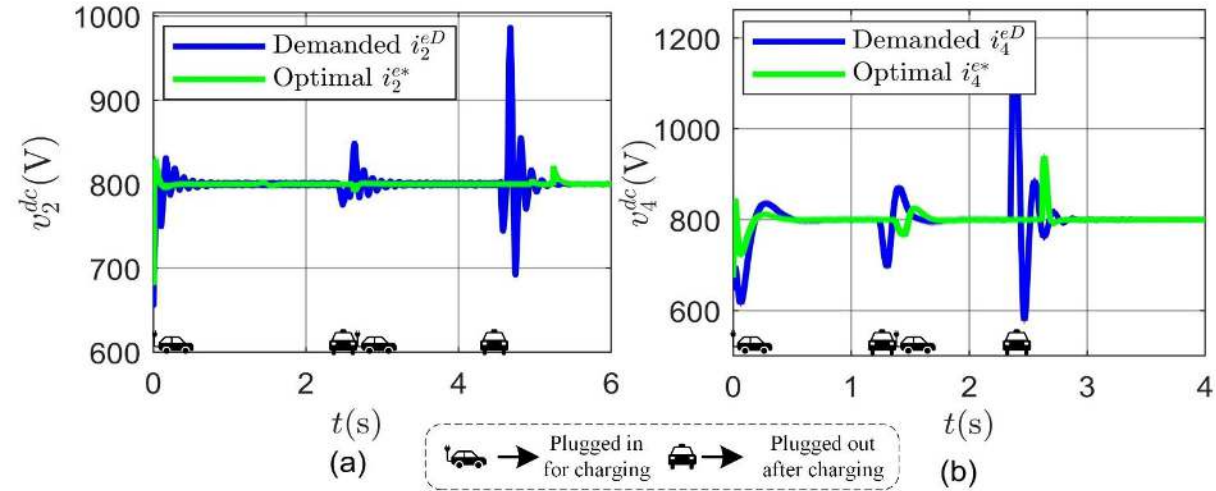


Figure: Comparison of DC bus voltage response with (a) $i_2^{eD} = 62.5A$, and $i_2^{e*} = 56.44A$, and (b) $i_4^{eD} = 125A$, and $i_4^{e*} = 116.53A$

60% improvement

System \mathcal{H}_2 -norm reduces from 0.0015 to 5.928e-4

Reduced system norm makes system **less sensitive to EV load disturbance**

Multiport EVCSs

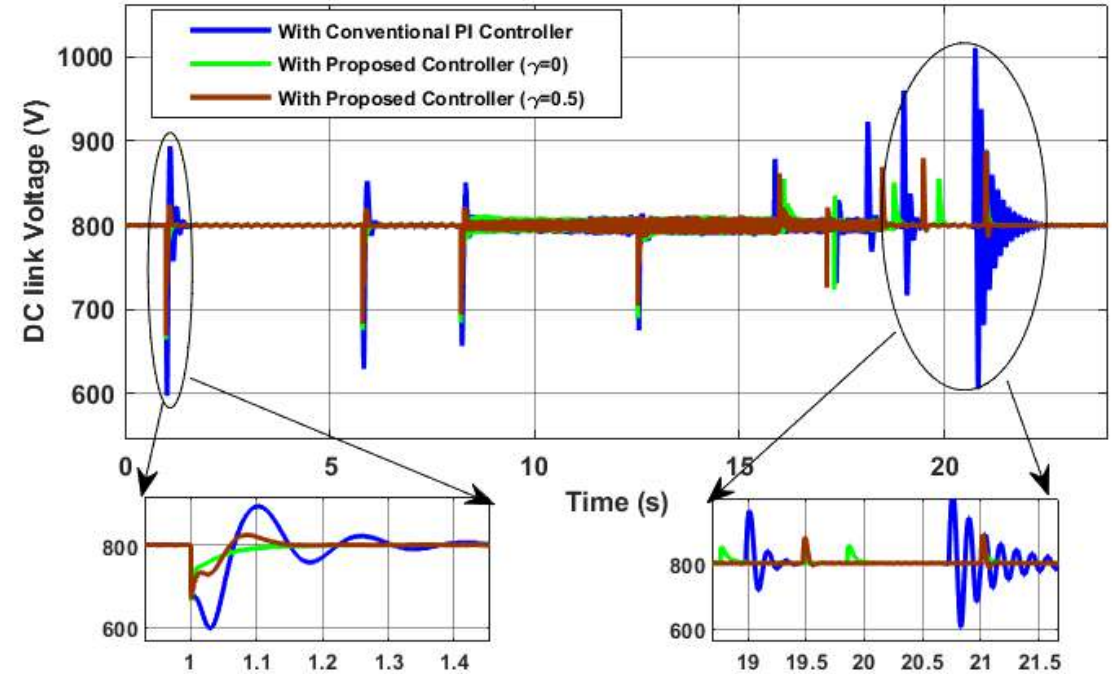


Figure: Comparison of DC bus voltage considering multi-port dynamics




The effectiveness of proposed optimal controller is much more evident in multi-port EVCSs

Both Uni- and Bi-directional EVCS Case




Table: Data table while variation in prioritization

EVCS	Pc^D	Pc^*	W^t	I^e	$\sum I^e$	$\ G_{ie}\ _{\mathcal{H}_2}^2$	\mathcal{V}_{\min}
Case 1: $\gamma_1 = 0, \gamma_2 = 0$							
1	50	42.5	19.06	6.35	51.47	9.65e-4 {9.71e-4}	0.630
2	100	85	9.53	7.94			
3	100	86.85	8.18	6.82			
4	(175)	(164.88)	1.89	2.75			
5	(150)	(143.15)	1.72	2.15			
6	(175)	(169.83)	0.94	1.37			
7	50	42.5	19.06	6.35			
8	100	85.94	8.83	7.36			
9	50	42.5	19.06	6.35			
10	100	91.77	4.84	4.03			
Case 2: $\gamma_1 = 0.33, \gamma_2 = 0.33$							
1	50	45.87	9.72	3.24	19.37	1.5e-3 {1.53e-3}	0.691
2	100	94.83	2.94	2.45			
3	100	95.91	2.30	1.92			
4	(175)	(171.83)	0.55	0.80			
5	(150)	(147.84)	0.53	0.66			
6	(175)	(173.38)	0.29	0.42			
7	50	44.98	12.05	4.02			
8	100	95.63	2.47	2.06			
9	50	46.63	7.81	2.60			
10	100	97.42	1.43	1.20			
Case 3: $\gamma_1 = 0, \gamma_2 = 0.6$							
1	50	42.75	18.32	6.10	37.13	1.6e-3 {1.64e-3}	0.770
2	100	92.11	4.63	3.86			
3	100	92.73	4.23	3.53			
4	(175)	(168.38)	1.21	1.76			
5	(150)	(144.11)	1.47	1.84			
6	(175)	(169.45)	1.01	1.47			
7	50	42.5	19.06	6.35			
8	100	92.53	4.36	3.63			
9	50	43.24	16.88	5.63			
10	100	93.81	3.56	2.96			




➡ Prioritization on small signal stability index


System \mathcal{H}_2 norm 9.65×10^{-4} 
 VSI \mathcal{V}_{\min} 0.63 
 Incentives $\sum I^e$ 51.47 

➡ Equal priority on all three index

System \mathcal{H}_2 norm 1.5×10^{-3} 
 VSI \mathcal{V}_{\min} 0.691 
 Incentives $\sum I^e$ 19.37 

➡ Prioritization on voltage stability index

System \mathcal{H}_2 norm 1.6×10^{-3} 
 VSI \mathcal{V}_{\min} 0.770 
 Incentives $\sum I^e$ 37.13 

Uncertainty analysis
 We run the proposed algorithm on the nominal test system model but apply the solution with a **30% increase** in all non-EV loads.
Result
 Only **0.62%, 2%, and 2.5% higher** than their respective nominal values

 Denotes **low sensitivity** to model uncertainty

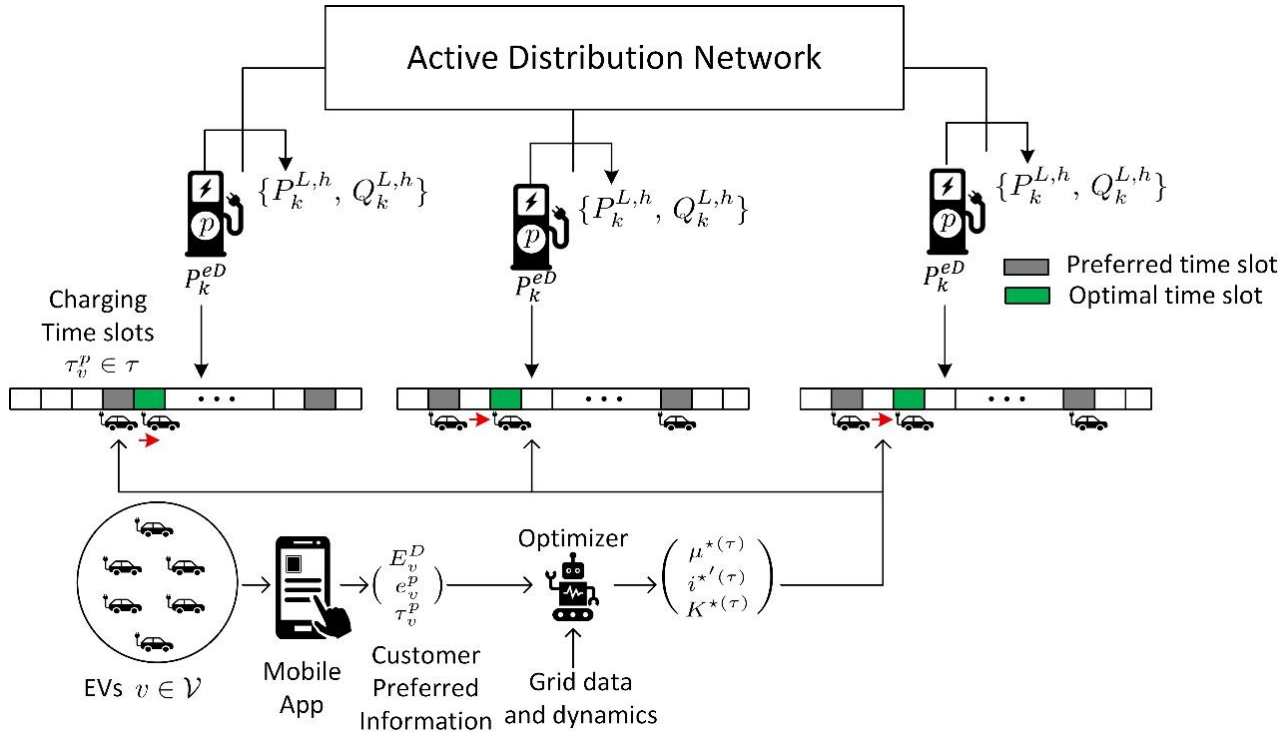
Problem 2

Finite Time Horizon Problem

Our aim is to consider more comprehensive "EVCS-EV" interaction while designing the problem

The operating point of the EVCS-EV integrated grid depends on

- (i) Which EV is connected to which EVCSs?
- (ii) Which time slot does each EV charge at its pre-specified EVCS?
- (iii) How much charging current is used at each EVCS?



Outcome:

{

 Optimal charging rate $i^{*'}(\tau)$

 Optimal feedback gain $K(\tau)$

 Optimal time slot $\{\tau_v^*\}_{v \in V}$
 }
 For each EV at each time slot



Implemented via "Wait & Save + Time Shifting" Incentive

Figure: A conceptual diagram of finite time horizon problem

Consumer Declaration

On the day before charging, each EV $v \in \mathcal{V}$ submits

- (i) its preferred EVCS $e_v^p \in \mathcal{E}$,
- (ii) its preferred arrival time slot $\tau_v^p \in \mathcal{T}$,
- (iii) Its energy request E_v^D [kWh]

EVCS Declaration

EVCS owner $e_v^p \in \mathcal{E}$, submits

- $\{i_e^{\max}, i_e^{\min}, \}$ \rightarrow Minimum & Maximum Charging rate
- $\pi_e \rightarrow$ per-kWh energy price

CPO's Objective

- (i) Based on $\{\tau_v^p, i_v^{\max}, i_v^{\min}\}$ for $v \in \mathcal{V}$, the CPO determines an optimal charging-current vector $i^{*(\tau)}$ to improve **damping performance** under a state feedback control $u^{(\tau)}(t) = -K^{(\tau)}\hat{x}^{(\tau)}(t)$

$$J_0(i^{*(\tau)}, \mu^{(\tau)}) := \|G_{i^{*(\tau)}, \mu^{(\tau)}}\|_{\mathcal{H}_2}^2,$$

- (ii) Keep the **voltage stability margin** by

$$J_1(i^{*(\tau)}, \mu^{(\tau)}, \tau) := \|\mathbf{1}_{|\mathcal{N}_{\text{rec}}|} - \text{VSI}(i^{*(\tau)}, \mu^{(\tau)}, \tau)\|_{\infty, \beta^{\text{VSI}}}$$

- (iii) Keep the **consumer satisfaction** by the incentive term

$$J_2(i^{*(\tau)}, \mu^{(\tau)}, \tau) := \sum_{v \in \mathcal{V}} \mu_v^{(\tau)} \left(M_v^C(i_v^{*(\tau)}) + M_v^S(\tau) \right).$$

Where,

Wait & Save Incentive

$$M_v^C(i_v^{*(\tau)}) := C_v^D \frac{T_v^{*(\tau)} - T_v^{\min}}{T_v^{\min}}$$

Time Shifting Incentive

$$M_v^S(\tau) := \beta_v^S E_v^D |\tau - \tau_v^p|$$

By balancing the above functions J_0, J_1 and J_2 using constant weights $\gamma_1 \in [0, 1]$ and $\gamma_2 \in [0, 1]$ such that $\gamma_1 + \gamma_2 \leq 1$ we define the **CPO's objective function** as

$$J^{(\tau)}(i^{*(\tau)}, \mu^{(\tau)}) := (1 - \gamma_1 - \gamma_2)J_0(i^{*(\tau)}, \mu^{(\tau)}) + \gamma_1 J_1(i^{*(\tau)}, \mu^{(\tau)}, \tau) + \gamma_2 J_2(i^{*(\tau)}, \mu^{(\tau)}, \tau)$$

Main Optimization Problem

$$\min_{\{K^{(\tau)}, i^{*(\tau)}, \mu^{(\tau)}\}_{\tau \in \mathcal{T}}} \sum_{\tau \in \mathcal{T}} J^{(\tau)}(i^{*(\tau)}, \mu^{(\tau)})$$

Such that

System model and control constraints

$$\sum_{\tau \in \mathcal{T}} \mu_v^{(\tau)} = 1, \quad \mu_v^{(\tau)} \in \{0, 1\}, \quad v \in \mathcal{V}, \quad \tau \in \mathcal{T} \quad \Rightarrow \quad \text{Unique time slot per EV}$$

$$\sum_{v \in \mathcal{V}_e} \mu_v^{(\tau)} \leq 1, \quad \forall e \in \mathcal{E}, \quad \forall \tau \in \mathcal{T} \text{ where } \mathcal{V}_e := \{v' \in \mathcal{V} \mid e_{v'}^p = e\}. \quad \Rightarrow \quad \text{Only one EV per EVCS per time slot}$$

$$\begin{cases} i_v^{*(\tau)} = 0, & \text{if } \mu_v^{(\tau)} = 0 \\ i_v^{*(\tau)} \in [i_v^{\min}, i_v^{\max}], & \text{otherwise} \end{cases}, \quad v \in \mathcal{V}, \quad \tau \in \mathcal{T}. \quad \Rightarrow \quad \begin{array}{l} \text{No connection to EVCS means no charging} \\ \text{Charging rate must lie within the allowable range} \end{array}$$



Given the complicated (nonconvex) optimization landscape, obtaining a globally optimal solution is challenging. Instead, we numerically find an **approximate stationary point**, which yield improved values of

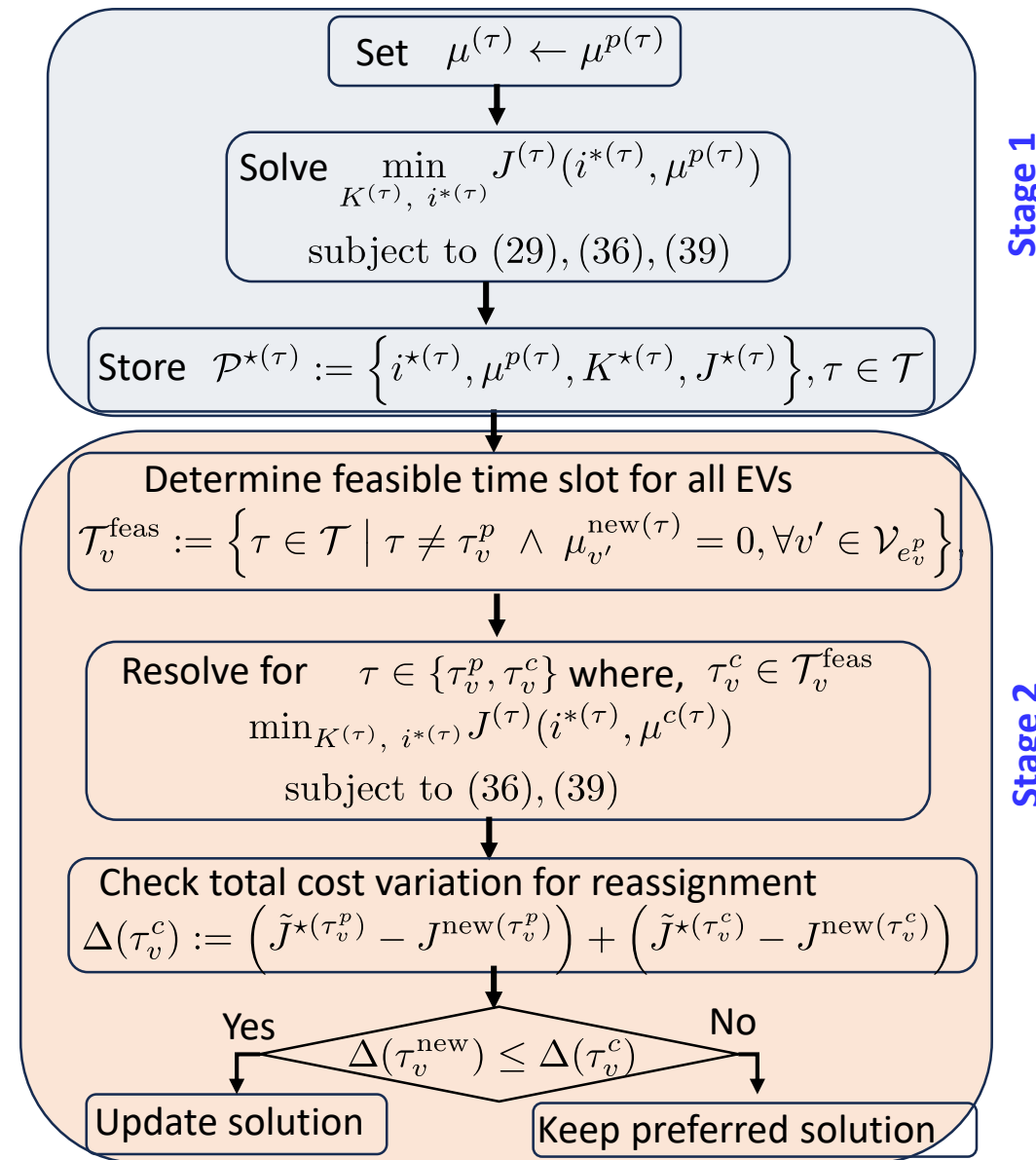
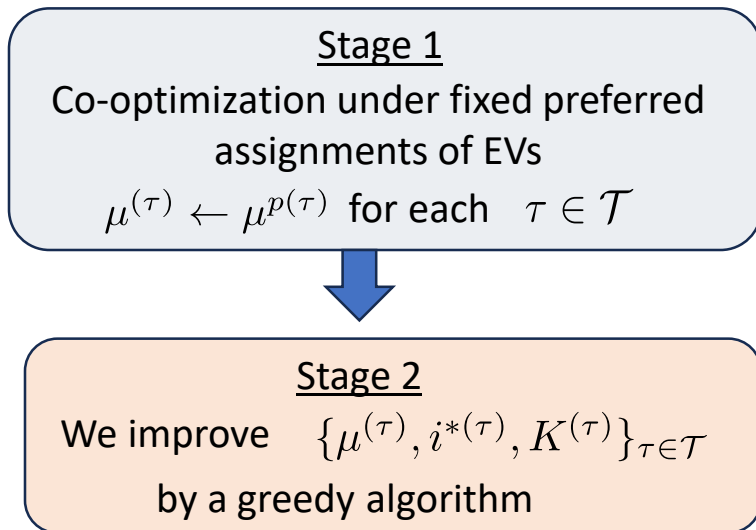
$$\{K^{(\tau)}, i^{*(\tau)}, \mu^{(\tau)}\}_{\tau \in \mathcal{T}}$$

Based on the declared customer information $\{e_v^p, \tau_v^p\}_{v \in \mathcal{V}}$ the CPO can uniquely construct *preferred assignment* of all EVs for each time slot as

$$\mu_v^{p(\tau)} := \begin{cases} 1 & \text{if } \tau = \tau_v^p \\ 0 & \text{otherwise} \end{cases}, \quad v \in \mathcal{V}, \quad \tau \in \mathcal{T},$$

and $\mu^{p(\tau)} := [\mu_1^{p(\tau)}, \dots, \mu_{N_V}^{p(\tau)}]^\top \in \{0, 1\}^{N_V}$

Now, to solve the optimization problem, we employ the following *two-stage algorithm*



Incentive Computation

For each EV, the CPO determines the incentives for charging-current change and time-shifting as follows

$$M_v^{C^*} := M_v^C(i_v^{*(\tau_v^*)}), \quad M_v^{S^*} := M_v^S(\tau_v^*), \quad v \in \mathcal{V},$$

The net amount of charging cost offered to EV will be

$$C_v^{\text{net}} := C_v^D - M_v^*, \quad M_v^* := M_v^{C^*} + M_v^{S^*}$$

Customer Selection

The CPO offer **three options** to EV consumers via mobile app

Option 1: Charge at preferred rate and time slot with no incentives

Option 2: Charge at optimal rate $i_v^{*(\tau_v^P)}$ at the preferred time slot with incentive $M_v^{C^*}$

Option 3: Charge at optimal rate $i_v^{*(\tau_v^P)}$ at the reassigned time slot with incentive M_v^*

Based on each EV's selection, the CPO updates the reassignment $\{\mu^{*'}(\tau), i^{*'}(\tau)\}_{\tau \in \mathcal{T}}$

Finally, the CPO implements $\{\mu^{*'}(\tau), i^{*'}(\tau), K^{*}(\tau)\}_{\tau \in \mathcal{T}}$ on the distribution grid

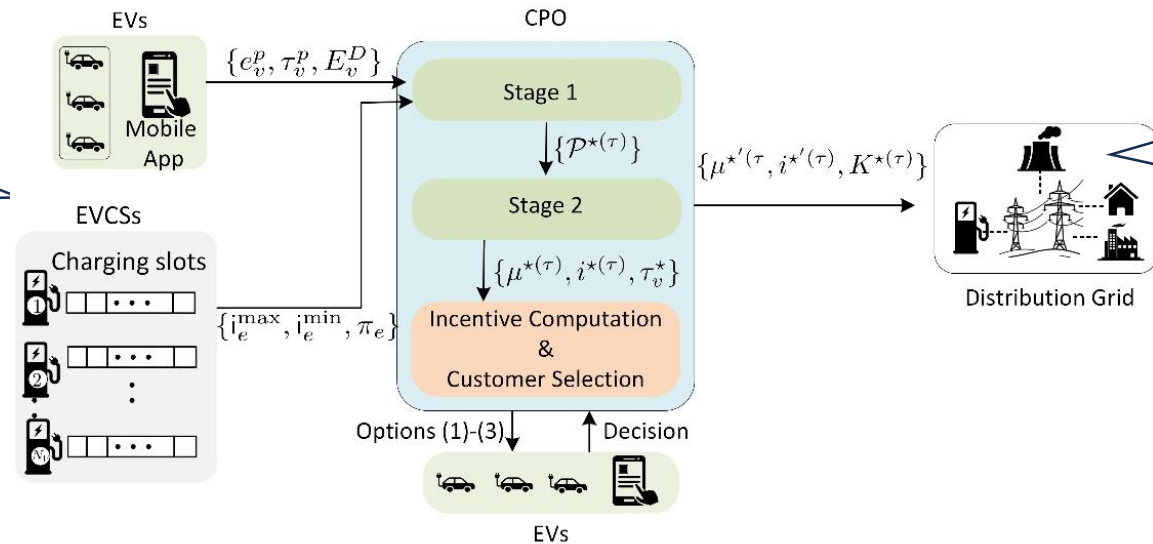


Figure: A schematic illustration of the whole proposed procedure.

Simulation Setup

We validate the proposed strategy using a modified IEEE 33-bus power distribution testbed, incorporating 10 EVCSs and three different non-EV loads.

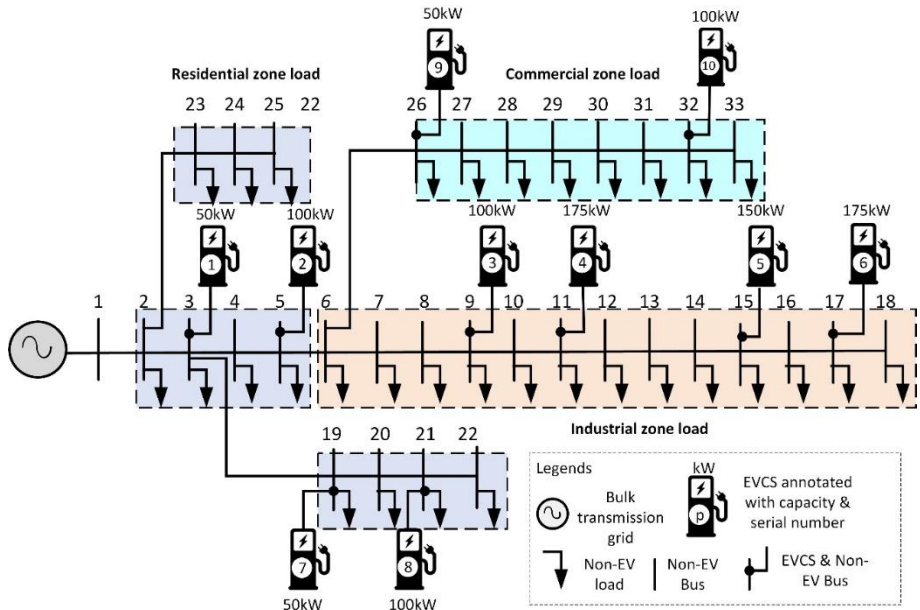


Figure. Modified IEEE 33 bus radial distribution network.

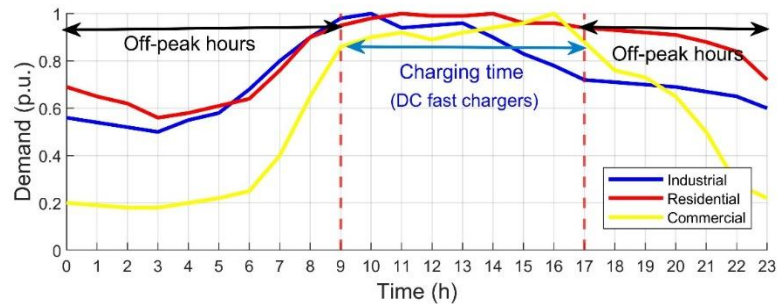
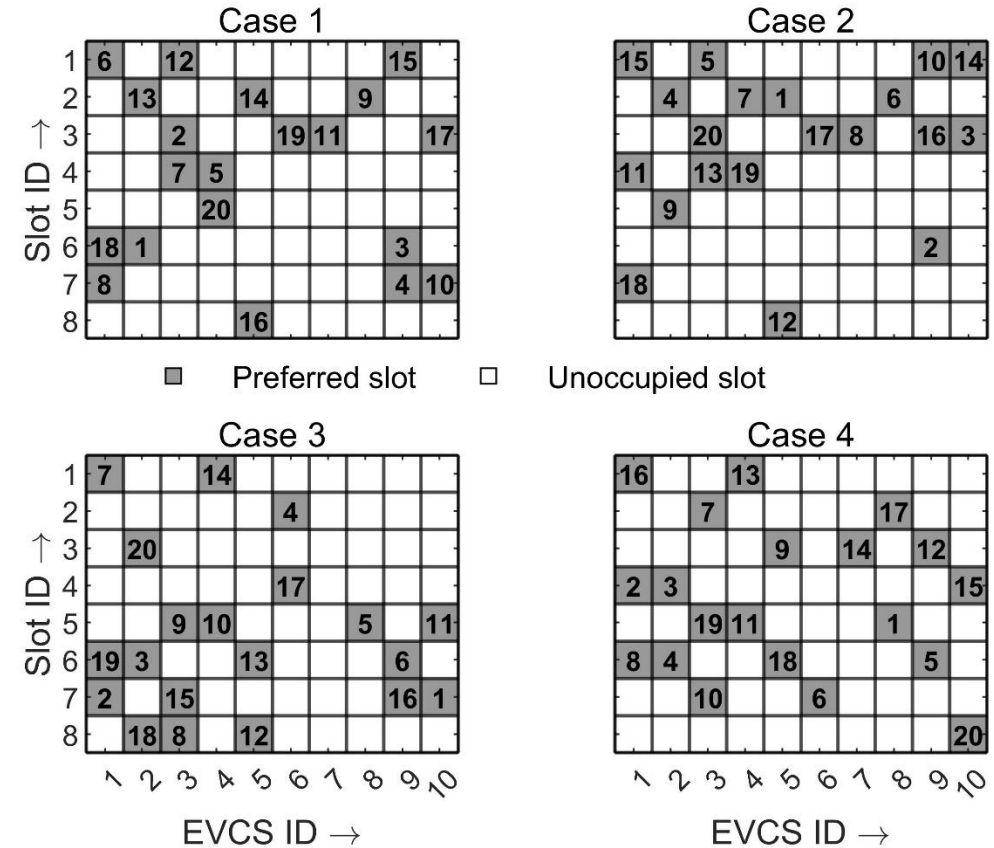


Figure. Typical daily load profiles for industrial (blue), residential (red), and commercial (green) sectors..

We consider the cases where 20 EVs will be connected during 9:00-17:00.

EV Consumers' Charging Preference



Case 1: Random hour

Case 2: Early morning

Case 3: Evening hour

Case 4: Midday hour

Negotiation via Proposed Incentivization Schemes

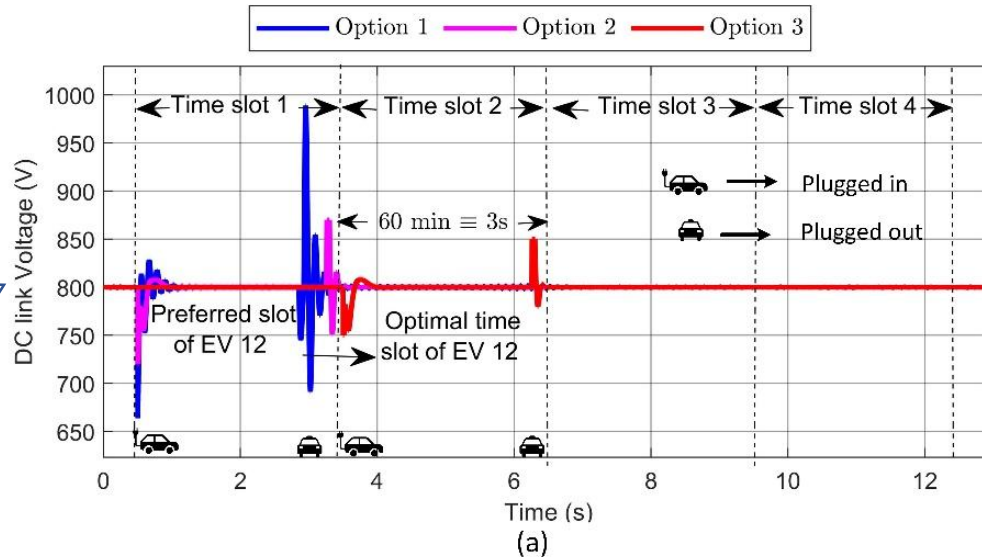
τ	At the preferred charging rate and time slot (Option 1)					At the preferred time slot with optimal charging rate (Option 2)						At optimal charging rate and time slot (Option 3)						
	v	i_v^{\max}	$g_1^{(\tau)}$	\underline{V}	M^{C*}	v	$i_v^{*(\tau)}$	$g_2^{(\tau)}$	\underline{V}	M_v^{C*}	M^{C*}	τ	v	$i_v^{*(\tau)}$	$g_3^{(\tau)}$	\underline{V}	M_v^*	M^*
1	6	62.5	1.09e-3	0.681	0	6	59.51	5.98e-4	0.709	1.02	31.51	1	13	89.37	4.35e-4	0.718	2.90	50.96
	12	187.5				181.38	1.52			14			120.54	3.46				
	15	187.5				182.43	1.25			15			182.23	1.25				
2	13	93.75	1.14e-3	0.701		13	89.38	5.87e-4	0.713	1.71		2	12	180.92	3.58e-4	0.724	3.46	
	14	125				121.43	1.32			9			120.05	1.85				
	9	125				120.05	1.85			6			58.91	3.03				
3	2	187.5	1.31e-3	0.662		2	178.1	7.92e-4	0.681	2.37		3	2	178.1	5.85e-4	0.694	2.37	
	19	93.75				89.67	1.02			11			59.45	1.04				
	11	62.5				59.45	1.04			17			58.4	1.42				
	17	62.5				58.4	1.42			18			57.54	3.54				
4	7	187.5	1.16e-3	0.665		7	177.43	8.54e-4	0.685	2.55		4	5	210.93	6.81e-4	0.691	1.67	
	5	218.75				210.93	1.67			19			89.11	2.97				
5	20	218.75	1.13e-3	0.691		20	210.51	8.33e-4	0.715	2.27		5	7	176.35	5.83e-4	0.728	4.64	
6	3	187.5	1.14e-3	0.661		3	176.65	7.53e-4	0.682	2.76		6	8	58.45	5.84e-4	0.692	3.76	
	18	62.5				57.95	1.59			1			89.45	1.1				
	1	93.75				89.45	1.1			3			176.65	2.76				
7	8	62.5	1.19e-3	0.659		8	59.25	7.25e-4	0.683	1.1		7	20	209.6	5.52e-4	0.695	3.76	
	4	187.5				181.83	1.4			10			58.52	1.4				
	10	62.5			58.52	1.4	16			121.87	1.15							
8	16	125	1.01e-3	0.71	16	121.87	6.93e-4	0.72	1.15	8	4	180.93	5.45e-4	0.731	3.43			

System norm minimized and VSI improved in exchange for a modest incentive payout

Further improvement in system norm and VSI for charging time slot adjustment and slightly more incentive

Time-domain response

The proposed optimal **option 3** ensures significant grid robustness if the EV customer agrees to change their original preferred EV charging time slot.



In a specific time-slot, the EV customer's **accept/reject** decision plays significant role in maintaining grid robustness.

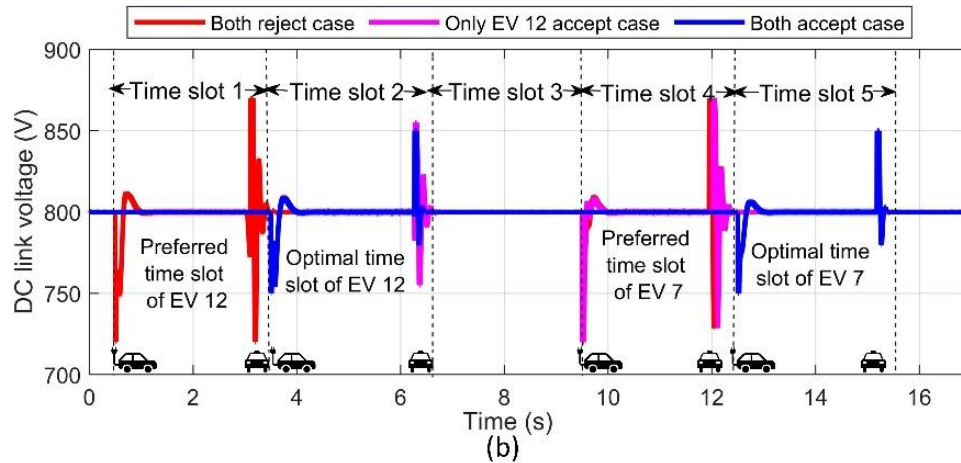


Figure: Transient DC link voltage profiles under representative EV charging scenarios: (a) comparison of system under three options, (b) impact on system response based on EV consumer decision for EV charging

- Our developed detailed **nonlinear state-space model** identified that integrating multiple EVCSs pops out several **semi-fast oscillatory modes with poor damping**, which need a proper control strategy to tackle this issue.
- We proposed a **co-optimization control strategy** that leverages the bidirectional capability of the EVCSs and provides a balance among small signal stability, user satisfaction via financial incentives, and voltage stability of the power distribution grid.
- We developed a **finite-horizon greedy heuristic-based optimal temporal scheduling framework** that could simultaneously provide optimal charging setpoints and a schedule for each EV, while offering incentives communicated via a mobile app.

The following future works can be carried out to extend the presented research works:

- We mainly considered two types of flexibility: One is the *demand flexibility*, and the other is *temporal flexibility*. The next type of flexibility may be *spatial flexibility*, where the optimal routing of large fleets of EVs will be coordinated to coexist on roads and highways with fleets of combustion engine vehicles within a given geographical region.
- A natural extension of our proposed methods will be to *more complex models of the distribution grid*, including
- various other **distributed energy resources** such as wind, solar, and energy storage,
 - **numerous distinct loads** such as **AI data center loads**, **high-performance quantum computing loads**, hydrogen processing facilities, and so on.



Thank You for Your Kind Attention 😊

Q & A

Solution Approach of Problem 1

