Optimal Charging and Discharging Scheduling of On-Board EV Chargers and ESS Considering Distribution Line Capacity, Building Load Imbalance and Peak Shaving

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Contents

Introduction

❖ Increase On-board Charger EV Penetration

- Most EVs will charge their battery at night time
  - Required ISO to increase line capacity
- High load density at specific time period
  - Voltage drop and Increase of line loss
- Connected to three-phase randomly
  - three-phase load imbalance of a building

➡ EV charging scheduling considering line capacity and three-phase load imbalance

❖ Increase Energy Storage System (ESS) in distribution System

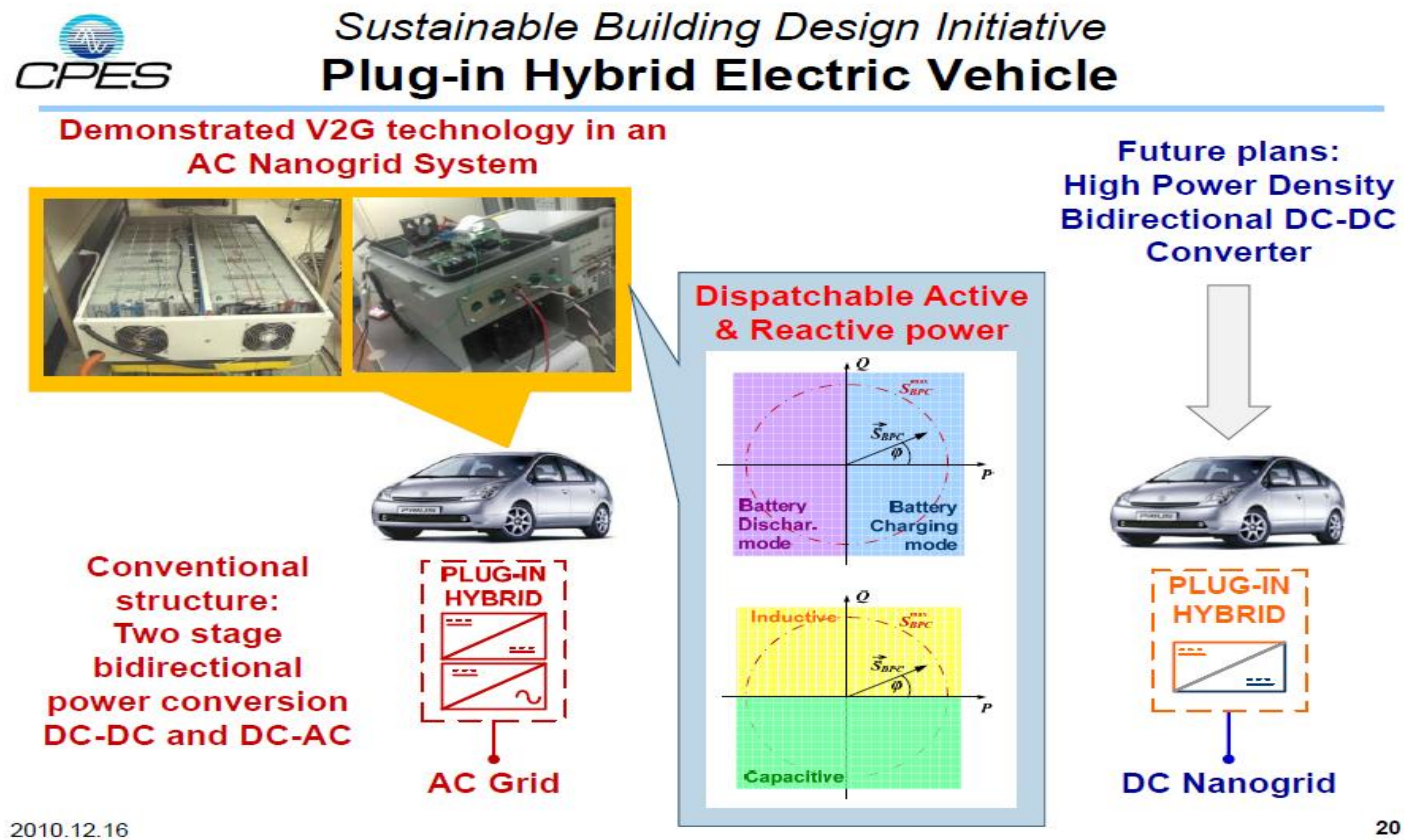
- ESS can be utilized for peak shaving, frequency control, and etc.

Introduction

❖ Proposed on-board EV charger and ESS charging and discharging scheduling

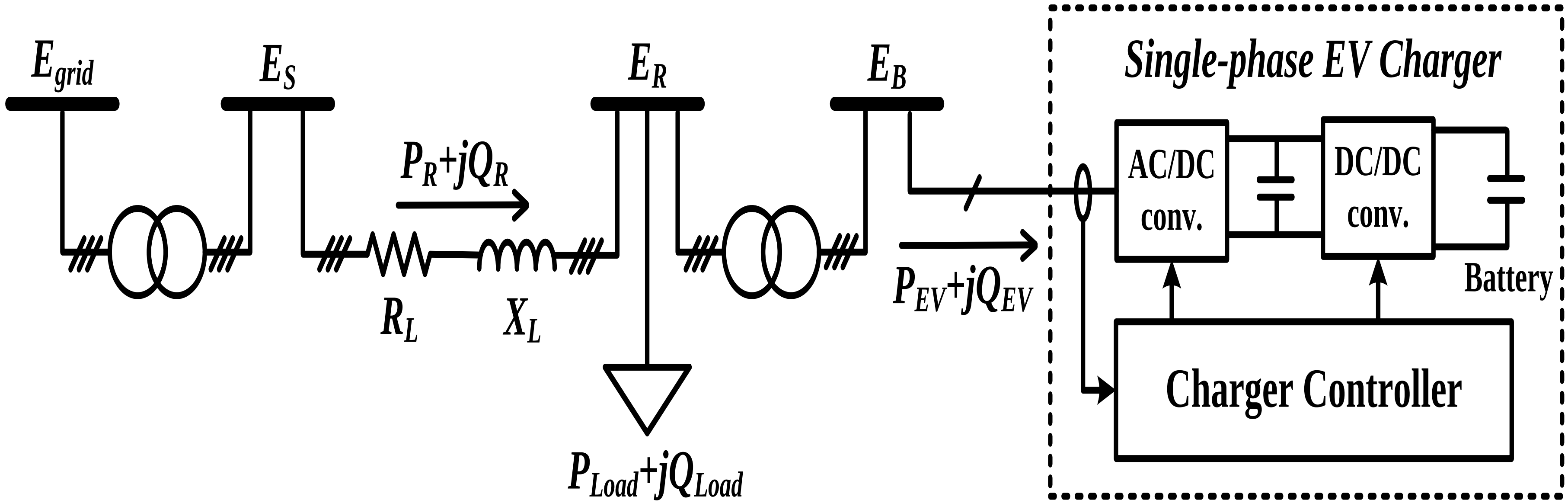
- Objective
  - Avoid a line overload and reduce the total distribution line loss
  - Reduce a three-phase load imbalance
  - Peak shaving at day time
- Assumption
  - ISO can control PEVs charging by using a building aggregator
  - Inverters of on-board charger are able to control their power factor
  - The difference between actual and forecasted load data is small
- Optimization
  - Sequential Linear Programming (SLP)
  - Use loss sensitivity for linearizing a objective function

EV can provide a reactive power



Voltage control and power loss with respect to EV

❖ Simplified distribution power system



- Load : constant power load
- EV Charger : provide or absorb P_{EV} and Q_{EV} when a bus voltages is maintained within the rated voltage

Voltage control and power loss with respect to EV

- E_S, E_R, P_{Loss} can be functionally expressed as P_{EV}, Q_{EV}

  - $E_R = \sqrt{\frac{E_S^2-2(R_LP_R+X_LQ_R)\pm\sqrt{8R_LX_LP_RQ_R-4E_S^2(R_LP_R+X_LQ_R)+E_S^4-4\left(R_L^2Q_R^2+X_L^2P_R^2\right)}}{2}}$

  - $E_S = \sqrt{E_R^2 + 2(R_LP_R + X_LQ_R) + \frac{(R_L^2+X_L^2)(P_R^2+Q_R^2)}{E_R^2}}$

    - $E_R = f_1(P_R, Q_R) = f_2(P_{EVs}, Q_{EVs})$, $E_s = g_1(P_R, Q_R) = g_2(P_{EVs}, Q_{EVs})$
    - $P_R + jQ_R = (P_{Load} + P_{EVs}) + j(Q_{Load} - Q_{EVs})$

  - $P_{Loss} = \left|\tilde{I}_R\right|^2 R_L = \left|\frac{P_R-jQ_R}{E_R}\right|^2 R_L = \left|\frac{(P_{Load}+P_{EVs})-j(Q_{Load}-Q_{EVs})}{E_R}\right| R_L = h_1(P_{EVs}, Q_{EVs})$

  - **EVs can provide reactive power to system when they are idle**
  - **Maintain a bus voltage and reduce line loss by charging EVs**

EV and ESS Charging and Discharging Scheduling

❖ Scheduling formulation for EV and ESS

- **Objective Function : Minimize the total distribution line loss**
  - ➢ Minimize a increasing loss caused by EV and ESS charging at base load
  - ➢ Use loss sensitivity due to EV and ESS charging

$$J = Min\left(\sum_{h=1}^{N} \Delta P_{Loss}^{h}\right) = Min\left(\sum_{h=1}^{N} \left(P_{EV+Load}^{h} - P_{Load}^{h}\right) + \left(P_{ESS+Load}^{h} - P_{Load}^{h}\right)\right)$$

- **Constraints**
  - ➢ Limitation of Line capacity

$$\sqrt{\left(\sum_{i=1}^{N_P} P_i^h\right)^2 + \left(\sum_{i=1}^{N_P} Q_i^h\right)^2} \le \Delta S_{max}^{h}, \qquad \Delta S_{max}^{h} = S_{building}^{h} - S_{Load}^{h}$$

  - ➢ Three-phase load balance (EV building bus)

$$\sum_{i=1}^{N_P} P_{i,j}^{h} \ge \Delta P_{phase}^{h} \; for \; j = A, B, C, \qquad \Delta P_{phase}^{h} = \max_{\substack{phase \\ \text{A,B,C}}}\left\{\left|P_A^h - P_B^h\right|, \left|P_B^h - P_C^h\right|, \left|P_C^h - P_A^h\right|\right\}$$

EV and ESS Charging and Discharging Scheduling

❖ Scheduling formulation for EV

➢ **Limitation of Charger capacity**

$$\sqrt{(P_i^h)^2+(Q_i^h)^2} \le S_i^{charger} \ for\ all\ i_{th}\ EV$$

➢ **Full charge of PEVs**

$$\sum_{h=1}^{N_i^{charge}} P_i^h T = E_i \ \ for\ all\ i_{th}\ EV\ , T{:}\ time\ interval$$

➢ **Voltage magnitude limits**

$$V_{min} \le V_k^h \le V_{max}\ for\ h = 1,2,\cdots, N_T\ and\ k = 1,2,\cdots, N_B$$

➢ **ESS discharging for Peak shaving**

$$\sum_{i=1}^{N_P} P_{i,disc}^h + \sum_{i=1}^{N_{ESS}} P_{i,discESS}^h \ge P_{load,total}^h - P_{peak} \quad when\ P_{load}^h > P_{peak}$$

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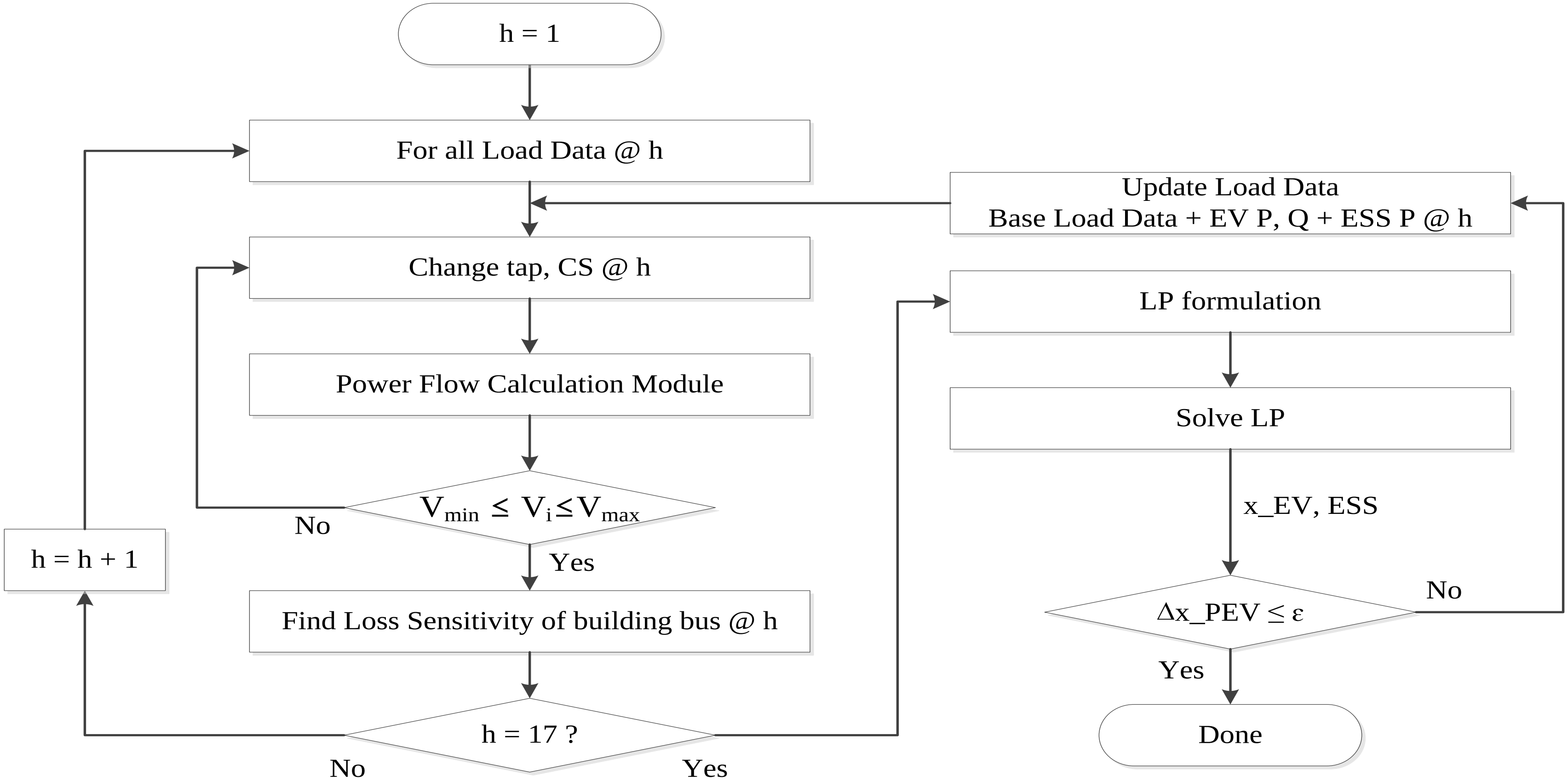
EV and ESS Charging and Discharging Scheduling

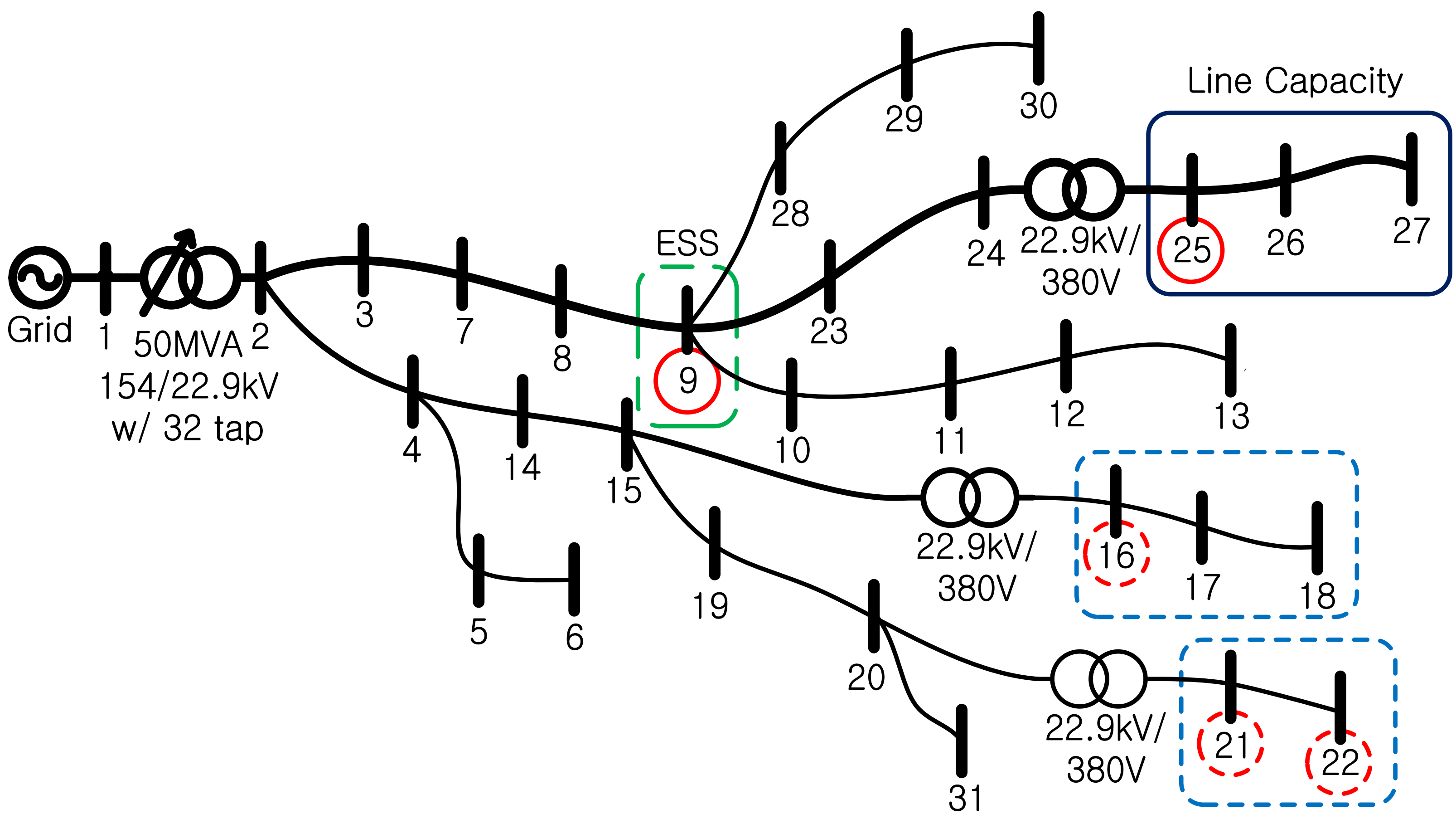
❖ SLP flow chart for EV and ESS scheduling

- Power Flow Calculation Module - Back/Forward Sweep PF Method



Case Study

❖ Test distribution system for simulation



Case Study

❖ Detailed specifications of the test system

Distribution Lines	Modified IEEE 30-bus test system
Transformer	3Ø, 154/22.9 kV, 50 MVA, x=8%, x/r = 20
ULTC	Installed at HV side, -10% to +10% LV regulation with 32 steps
Capacitors	Substation Capacitors : 0.2 MVAR each
Loads	At Bus 31 : 26 ~ 31 MW with 0.7~0.9 pf lag
Peak Reference	36.5MW
Building Max Line Cap.	4240kVA (5300kVA, margin 20%)
EVs	· Changeable PEV number : 94 ~ 114 PEVs · Initial SOC : 0.1 ~ 0.4 (Average : 0.25) · Charging Start Time : h = 1 ~ 3, Charging End Time : h = 5 ~ 8 · Rated charger Capacity : 4 kVA · Battery Capacity : 24, 28, and 30 kWh
ESSs	· Rate Power : 10MW · Capacity : 5MWh · Initial SOC : 0.5 · Final SOC : 0.5

Case Study

❖ EV scheduling when number of EVs are changed

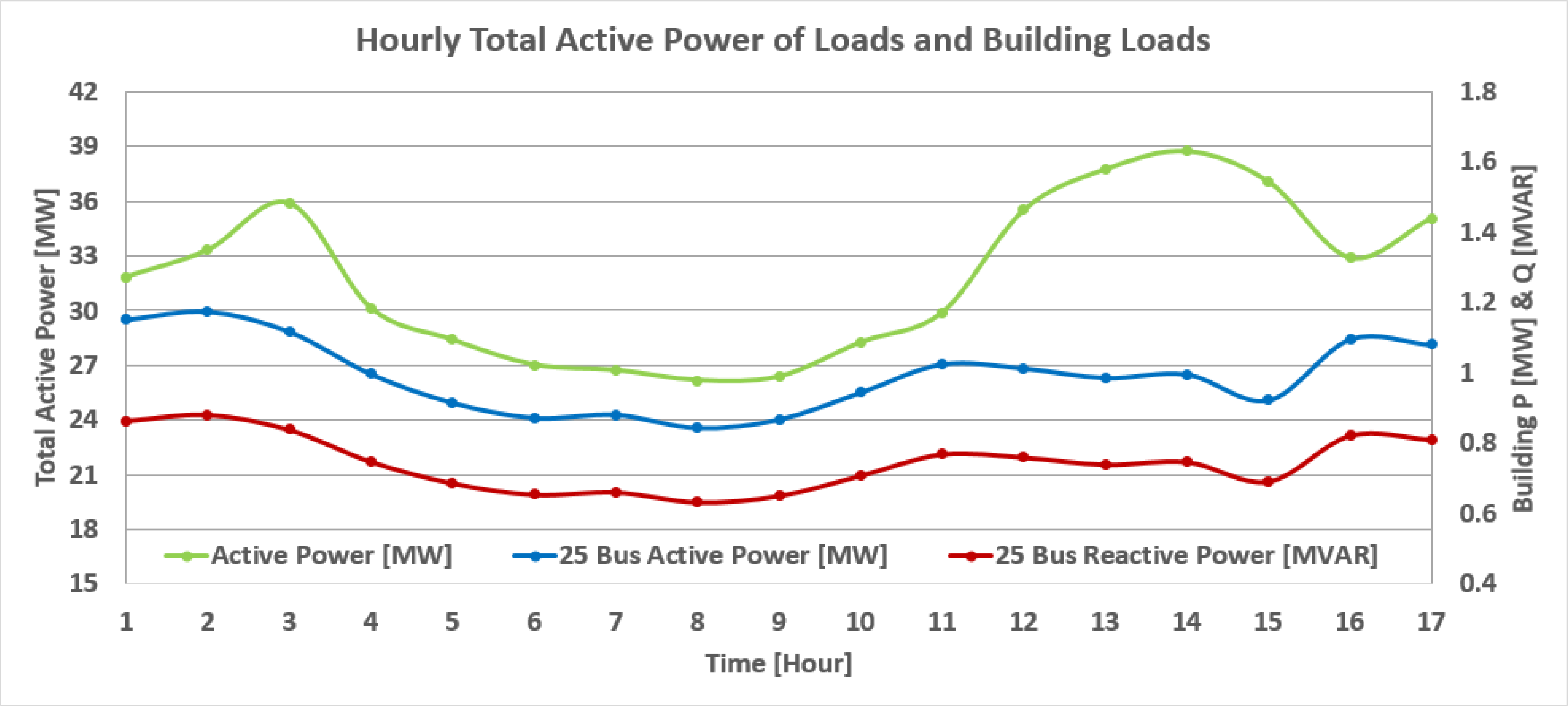
- Hourly change number of EVs

Hour	2(23h)	3(24h)	4(01h)	5(02h)	6(03h)	7(04h)	8(05h)	9(06h)
EV change	+5	+9	0	-10	-10	0	0	-4
Hour	10(07h)	11(08h)	12(09h)	13(10h)	14(11h)	15(12h)	16(13h)	17(14h)
EV change	-5	-25	-15	-12	-3	-5	0	+5

Case Study

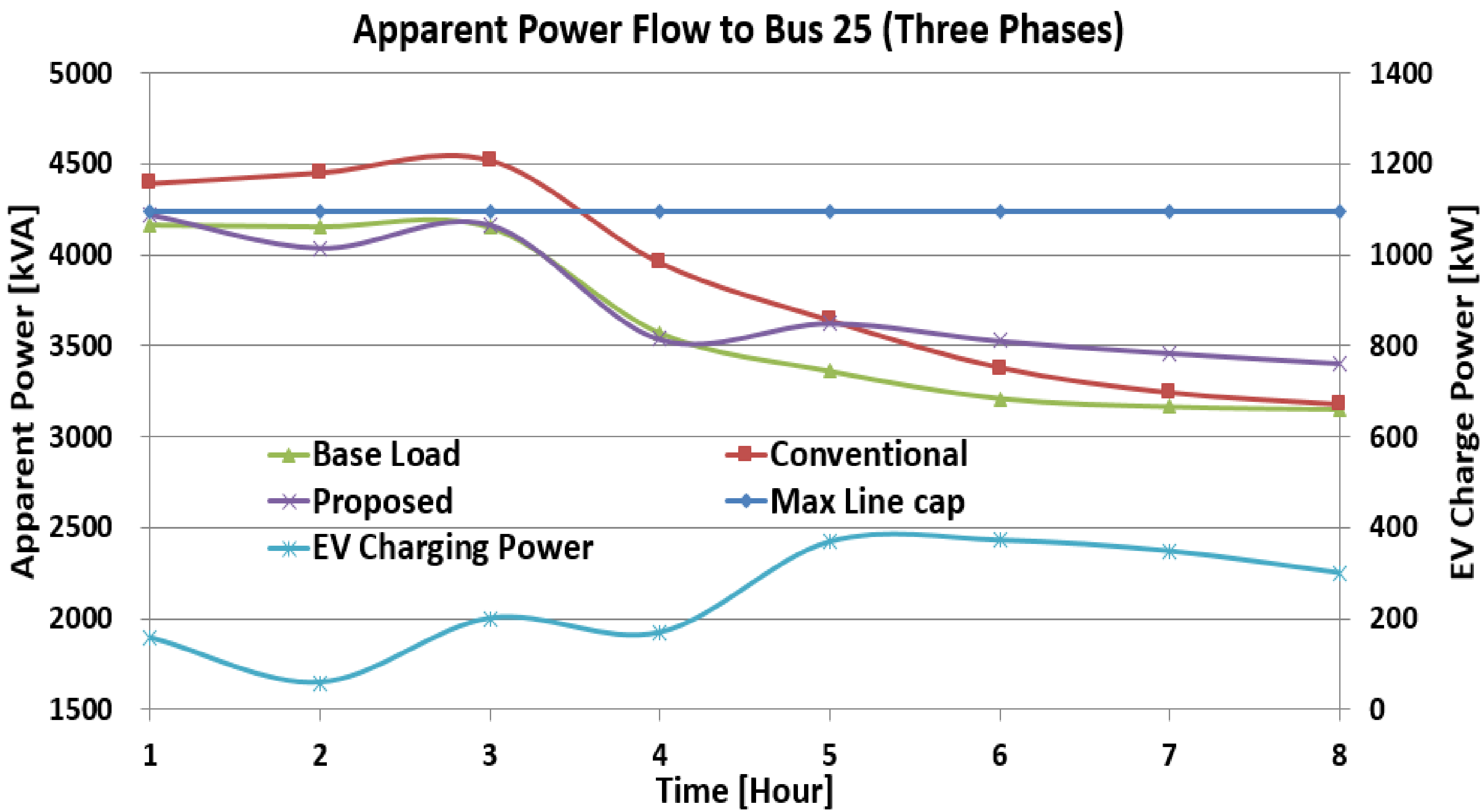
❖ Load Profile

- Scheduling Time : 22h – 14h (17 hours)
- Peak Load : 36 [MW], Total load capacity : 240 [MWh], average power factor : 0.8 pf lag,



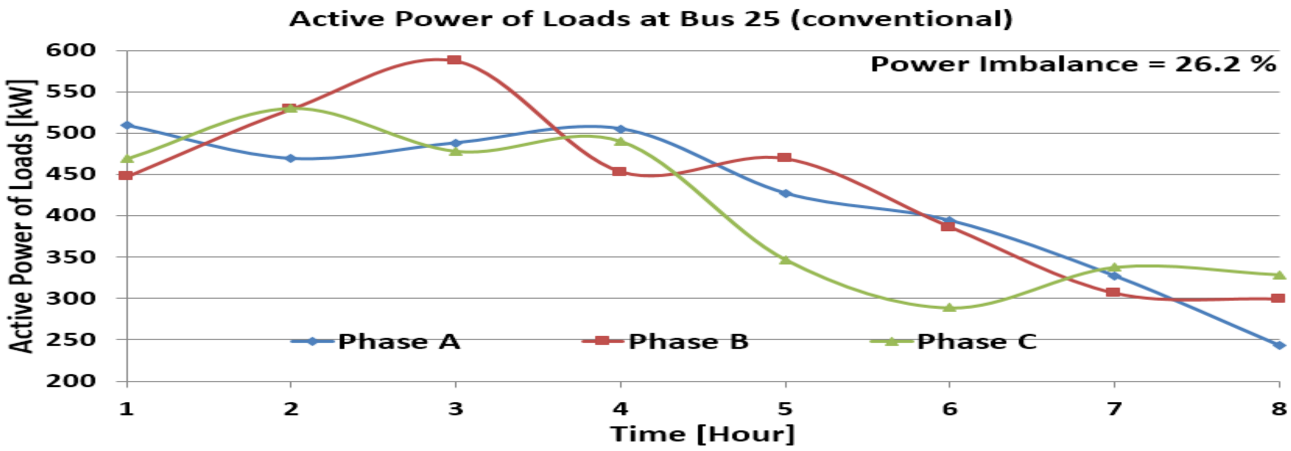
Case Study

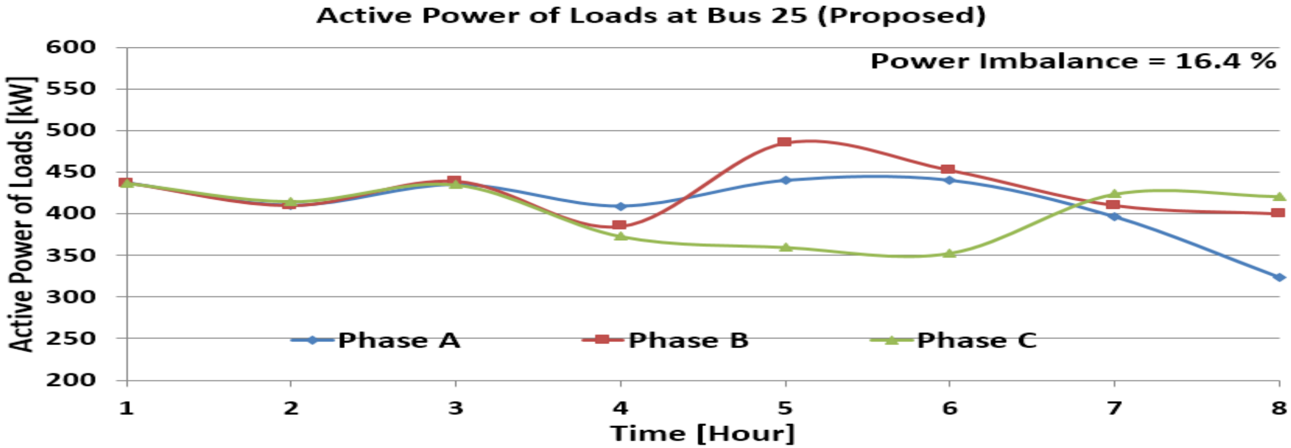
❖ Three-phase imbalanced EV charging scheduling



Case Study

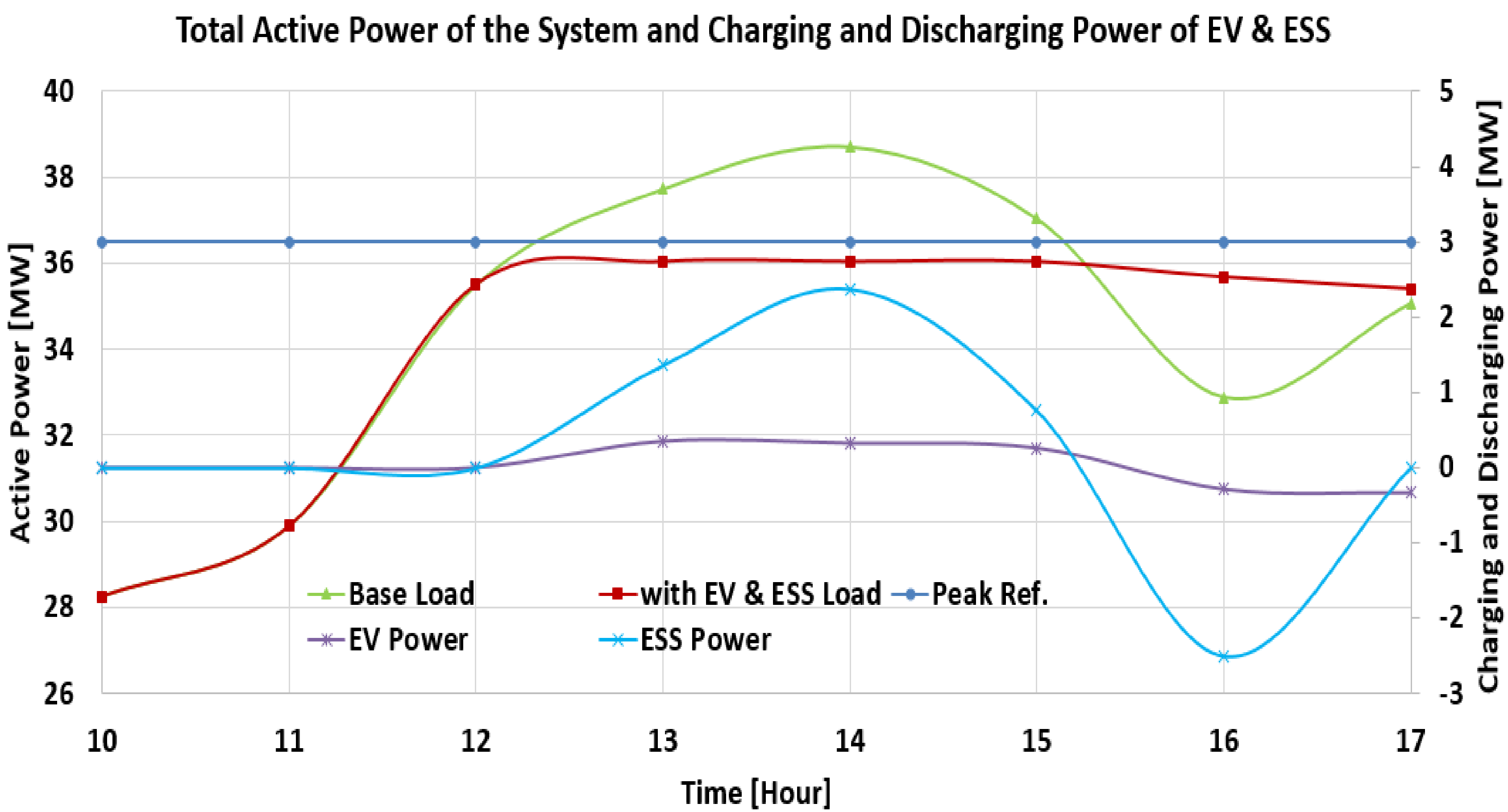
❖ Three-phase load imbalance





Case Study

❖ Peak shaving at day time by discharging EV and ESS



Case Study

❖ Total distribution line power loss

Loss	Conventional [kWh]	Proposed [kWh]	Reduced [%]
1 Building (Bus 25)	8.34	8.20	1.44
3 Buildings (Bus 16, 21 and 25)	8.50	7.97	6.24

Conclusion

- **Propose Onboard Charger EV and ESS charging and discharging scheduling**
  - Consider capability that EV provide reactive power
    - Avoid a line overload and reduce the total distribution line loss
    - Reduce a three-phase load imbalance
  - Discharge EV and ESS for peak shaving at day time

- **Theoretical analysis**
  - Problem formulations with respect to EV

- **Case Study**
  - Proposed method is capable of achieving its objective effectively

Thank you