Low-Voltage Consumption Coordination for Loss Minimization and Voltage Control

Smart & Cool project

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Smart and Cool Meeting, DTU, 10/06/2013
This talk

- coordination of residential consumption and production
- minimization of active power losses
- reduction of voltage variations
Background

Current consumption trends:

- Increasing electrical load from electric vehicles (EVs), electric heat pumps (EHPs), etc.
- Increasing local production from photo-voltaics (PVs), household wind turbines, etc.

These tendencies cause:

- Increased grid loading and power losses
- Risk of grid congestion
- Risk of under voltages caused by increased consumption
- Risk of over voltages caused by increased production
Suggested solutions

- employing PV inverter for injecting/consuming reactive power
- local energy storage of excess solar power
- shedding solar panel output
- coordinating PV production against flexible consumption
Problem outline

we consider a radial in the low-voltage distribution grid:

- consumers are characterized by inflexible consumption as well as flexible consumption from EVs
- consumers further present local production from PVs
- grid imposes losses and voltage variations
Problem outline

- our goal is to minimize active losses as well as to ensure voltage quality over some period of time
- for this, we design trajectories for the controllable entities: $\tilde{q}_{pv}(t), \tilde{q}_{ev}(t), \tilde{p}_{ev}(t)$ for each household
Premises

- consider a discrete time period $\mathcal{T} \equiv \{1, \ldots, m\}$
- for each household $h \in H \equiv \{1, \ldots, n\}$ and $t \in \mathcal{T}$, let
  \[ p_h(t) = \overline{p}_h(t) + \tilde{p}_{ev,h}(t) - p_{pv,h}(t), \]
  \[ q_h(t) = \overline{q}_h(t) + \tilde{q}_{ev,h}(t) - \tilde{q}_{pv,h}(t). \]
- let there be provided known estimates of uncontrollable signals: $p_{pv}(t), \overline{p}(t), \overline{q}(t)$
the flexible consumption (EVs) present the constraints

\[ \sum_{t=t_{ev},h}^{m} T_s \tilde{p}_{ev,h}(t) + E_{ev,h}(t_{ev},h) = E_{dem,h}, \]

\[ E_{min,h} \leq \sum_{t=t_{ev},h}^{\tau} T_s \tilde{p}_{ev,h}(t) + E_{ev,h}(t_{ev},h) \leq E_{max,h}, \]

\[ p_{min,h} \leq \tilde{p}_{ev,h}(t) \leq p_{max,h}, \]

\[ \tilde{q}_{ev,h}(t) = \tilde{p}_{ev,h}(t) \tan(\cos(\psi_h)), \]

for each \( h \in H, t \in \mathcal{T} \), where \( t_{ev,h} \) is a time of availability and \( \psi_h \) is the EV power factor
Premises

the solar panel inverters present the constraint

$$|\tilde{q}_{pv,h}(t)| \leq \sqrt{s_{\text{max},h}^2 - p_{pv,h}(t)^2}, \quad \forall t \in \mathcal{T}$$

for each $h \in H$, $t \in \mathcal{T}$, where $s_{\text{max},h}$ is the maximum apparent power:

Figure: Constraint on PV inverter
Premises

maintaining voltage quality requires

\[ u_{\text{min}} \leq |u_h(t)| \leq u_{\text{max}}, \quad \forall t \in T, \, h \in H, \]

visualized as:

**Figure:** Allowed voltage range
active losses and voltage drops

- let $i(t) = (i_1(t), \ldots, i_n(t))$ and $u(t) = (u_1(t), \ldots, u_n(t))$
- considering radials with tree topology, the voltage for each consumer $u(t)$, and the active distribution loss $p_d(t)$, is expressed by

$$ p_d(t) = i(t)^\dagger J_r i(t) \quad \text{and} \quad u(t) = u_s - J_z i(t), $$

where $J_r, J_z$ are symmetric matrices, derived from the radial topology and grid impedances (loop impedance matrices)
Optimization problem

\[ \text{minimize \ } i_h(t), \tilde{p}_{ev,h}(t), \tilde{q}_{pv,h}(t) \]
\[ h \in H, \ t \in T \]
\[ \sum_{t=1}^{m} p_d(t) \]

subject to
\[ u_{\min} \leq |u(t)| \leq u_{\max}, \]
\[ p_{\min,h} \leq \tilde{p}_{ev,h}(t) \leq p_{\max,h}, \]
\[ T_s \sum_{t=t_{ev,h}}^{m} \tilde{p}_{ev,h}(t) \in [\delta E_{\min,h}, \delta E_{\max,h}], \]
\[ T_s \sum_{t=t_{ev,h}}^{m} \tilde{p}_{ev,h}(t) = \delta E_{\text{dem},h}, \]
\[ \tilde{q}_{pv,h}(t) \leq \sqrt{s_{\max,h}^2 - p_{pv,h}(t)^2}, \]
\[ i_h(t) = \frac{p_h(t) - jq_h(t)}{u_h^\dagger(t)} \]
Simplified optimization problem

minimize \[ \sum_{t=1}^{m} p_d(t) \]
\[ i_h(t), \tilde{p}_{ev,h}(t), \tilde{q}_{pv,h}(t) \]
\[ h \in H, t \in T \]

subject to
\[ |u(t)| \leq u_{\text{max}}, \quad \text{Re}(u(t)) \geq u_{\text{min}} \]
\[ p_{\text{min},h} \leq \tilde{p}_{ev,h}(t) \leq p_{\text{max},h}, \]
\[ T_s \sum_{t=t_{ev,h}}^{m} \tilde{p}_{ev,h}(t) \in [\delta E_{\text{min},h}, \delta E_{\text{max},h}], \]
\[ T_s \sum_{t=t_{ev,h}}^{m} \tilde{p}_{ev,h}(t) = \delta E_{\text{dem},h}, \]
\[ \tilde{q}_{pv,h}(t) \leq \sqrt{s_{\text{max},h}^2 - p_{pv,h}^2(t)}, \]
\[ i_h(t) = \frac{p_h(t) - jq_h(t)}{\hat{u}_h^\dagger(t)} \]
Algorithm 1: Loss minimization procedure

initialize $\hat{u}(t) = 1$ pu, for all $t$, $\gamma = 1$, $\epsilon \in (0, 1)$

while $\gamma > \epsilon$ do

- solve simplified problem to obtain $i^*(t), q^*(t), p^*(t)$, for each $t$

- calculate true voltage:
  $u_{\text{true}}(t) = u_s - J_z i^*(t), \forall t \in \mathcal{T}$

- set $\gamma = \|u_{\text{true}}(t) - \hat{u}(t)\|$

- set $\hat{u}(t) = u_{\text{true}}(t)$, for all $t$

repeat

end
Numerical case study

consider the radial below, containing 34 consumers
Numerical case study

uncontrollable signals:

![Graphs showing uncontrollable signals](image)

**Figure:** Top: Inflexible consumption. Bottom: Baseline solar production.
Numerical case study

simulate two cases:

1. No solar power installed, some EVs installed
2. Some solar power installed, no EVs installed

benchmark/comparison strategy: EVs charge with max power when connected. No coordination among consumers are introduced
Numerical case study

benchmark/comparison results:

Figure: Top: Resulting voltage profile at each leaf by configuration 1 (solid), and allowed voltage range (dashed). Bottom: Similarly, voltage profiles by configuration 2.
Numerical case study

similar results for first case, when coordinating:

no improvement is obtained in case 2

Figure: Allowed voltage range (dashed), and resulting voltage profiles (solid).
Numerical case study

final case: 50% solar and EV penetration, randomly distributed:

Figure: Top: The total consumption. Middle: Corresponding EV charge schedule. Bottom: Resulting voltage profiles.
Concluding remarks

- coordinating flexible consumption, significantly reduces grid-loading and voltage drops
- over-voltages may also be avoided by coordinating flexible consumption and local production
- if no consumption can be coordinated to absorb local consumption, over-voltages may occur
- in that case, curtailment of local power production is a suggested approach
Thank you