Volt/Var Optimization with Minimum Equipment Operation under High PV Penetration

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  - Distribution Power Flow
  - Convexification
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Outline

Motivation

- The volatile net load profiles caused by increased deployment of penetration of photo-voltaic panels (PVs) in the distribution networks.
- The successive switching actions by conventional voltage control devices (switched capacitor banks (SCBs), on-load tap changers (OLTCs) and voltage regulators) to keep voltage magnitudes within limits.
- The need for coordination of PV inverter's reactive power generation/absorption with conventional devices.
- The need to abide by desired voltage limits at all buses, especially those of voltage-dependent loads.

Objectives

- Formulate a day-ahead optimization problem, centrally performed by distribution system operator (DSO), that finds a global optimal solution (optimal tap and capacitor setting and dispatch of PV VARs).
- Formulate linear models for OLTC and SCBs that exhibit their accurate switching behavior in response to voltage deviations from desired.
- Formulate an oversized PV inverter capable of generating/absorbing VARs up to 46% VARs of its nameplate during peak.
- Formulate an objective function that minimizes losses, flatten voltages (comply with CVR practices), and limit inter-temporal switching efforts of OLTC and SCBs.

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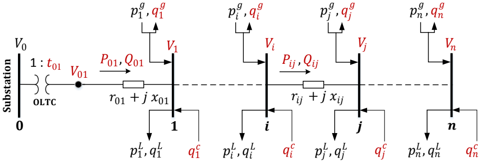
Distribution Power Flow



The following equations describe the non-linear power flows in radial distribution systems [1].

$$P_{ij} = \sum_{k:(j,k)\in\mathcal{E}} P_{jk} + r_{ij}\ell_{ij} + p_j^L - p_j^g \tag{1a}$$

$$Q_{ij} = \sum_{k:(j,k)\in\mathcal{E}} Q_{jk} + x_{ij}\ell_{ij} + q_j^L - q_j^g - q_j^c \tag{1b}$$

$$v_j = v_i - 2(r_{ij}P_{ij} + x_{ij}Q_{ij}) + (r_{ij}^2 + x_{ij}^2)\ell_{ij} \tag{1c}$$

$$\ell_{ij} = (P_{ij}^2 + Q_{ij}^2)/v_i \tag{1d}$$

P_{ij}, Q_{ij}: Power flows
v_i: Squared voltage
ℓ_{ij}: squared current
L: Load
g: PV power
c: SCB VAR

Convexification

- The problem in (1) is nonlinear, which is in general hard to solve and no off-the-shelf solver is available to guarantee neither convergence nor optimality.
- A second-order conic programming relaxation is proposed by **[2]** to modify (1d) as follows:

$$\ell_{ij} \geq (P_{ij}^2 + Q_{ij}^2)/v_i \tag{2a}$$

$$\left\| \begin{bmatrix} 2P_{ij} & 2Q_{ij} & \ell_{ij} - v_i \end{bmatrix}^T \right\|_2 \leq \ell_{ij} + v_i \tag{2b}$$

OLTC Model

The secondary-side voltage of the OLTC is increased/decreased by changing the turns ratio so as to affect the nodal voltages and power flows of the entire distribution system. The OLTC model is

$$t_{ij} = (t^{\min} + \Delta t_{ij} x) \qquad (3)$$

$$0 \leq x \leq x_{\max} \qquad \Delta t_{ij} = (t_{ij}^{\max} - t_{ij}^{\min})/x_{\max} \qquad (4)$$

t_{ij}: OLTC ratio
$t_{ij}^{\max}$ & $t_{ij}^{\min}$: Turns ratios,
Δt_{ij}: Change per tap
$x \in \mathcal{X}$: Tap position

A linearized version of the exact model can be obtained using binaries

$$T_{ij} = \sum_{x=0}^{\mathcal{X}} (t_{ij}^{\min} + \Delta t_{ij} x)^2 u_x \qquad \sum_{x=0}^{\mathcal{X}} u_x = 1 \qquad (5)$$

$$v_{ij} = T_{ij} v_i \qquad (6)$$

Binaries, u_x, are summed to one to force one selection of ratio

SCB Model

A set of switchable capacitors can be installed at the jth node, where each capacitor is switched on to increase the voltage at the node of installation and adjacent nodes.

$$0 \leqslant C_j \leqslant N_c \tag{7}$$

$$q_j^c = Q_c \frac{C_j}{N_c} \tag{8}$$

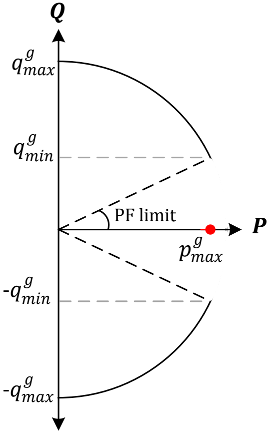
q_j^c: SCBs' variable
Q_c: Total VARs
N_c: Number of the SCB units

PV Model

In order to represent the operating points shown in the figure, the reactive-power constraint is expressed as

$$|q_i^g| \leqslant \sqrt{(s_i^g)^2 - (p_i^g)^2} \qquad (9)$$

where s_i^g is the inverter's nameplate, whereas p_i^g is the PV's forcasted active power.



Flatness/CVR limits

The following constraints are used to keep the voltage of the ith node between minimum and maximum thresholds.

$$z_i \geqslant 0, \quad z_i \geqslant v_i - (V_{i\,\min}^{thr})^2, \quad z_i \geqslant -v_i + (V_{i\,\max}^{thr})^2 \tag{10}$$

- Thresholds are chosen within $\pm 3\%$ to flatten. Bus voltages of voltage-dependent loads should be regulated within the lower half.
- The lower threshold is chosen as -3% to avoid excessive voltage drop the point of interconnection.
- z_i is minimized to keep voltages in the objective function.

Overall Problem

The overall optimization problem over T horizons is formulated as follows.

$$\begin{aligned}\text{min} \quad & f = \sum_{t}^{T} \Bigg(\lambda_{\text{loss}} \sum_{(i,j)\in\mathcal{E}} r_{ij}\ell_{t,ij} + \lambda_{\text{cvr}} \sum_{i\in\mathcal{N}_{\text{cvr}}} z_{t,i} \\ & + \lambda_{\text{flat}} \sum_{i\in\mathcal{N}-\mathcal{N}_{\text{cvr}}} z_{t,i} + \lambda_{\text{cap}} \sum_{i\in\mathcal{N}_{\text{cap}}} |C_{t,i} - C_{t-1,i}| \\ & + \lambda_{\text{tap}} \sum_{(i,j)\in\mathcal{E}_{\text{tap}}} |T_{t,ij} - T_{t-1,ij}| \Bigg) \\ \text{s.t.} \quad & (1a)-(1c), (2), (5)-(10)\end{aligned} \tag{11}$$

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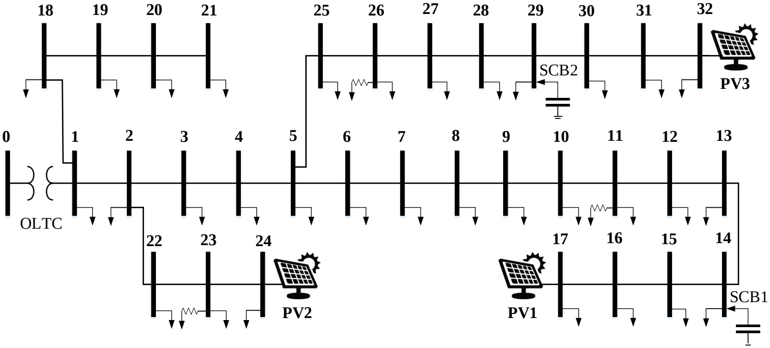
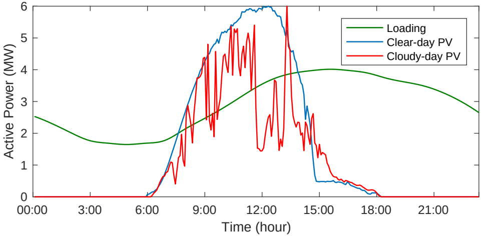
IEEE 33-bus system

Case studies on IEEE 33-bus system are conducted to highlight the following:

1. the impacts of cloudy day and clear day on the frequency of an OLTC's and SCBs' operations.
2. the effectiveness of the centralized VVO to mitigate the equipment operations and adhere to CVR limits by virtue of the inverter's inherent VAR capability.



System Specifications



- The original peak load is 4.55 MVA with power factor of 0.82.
- Three resistive loads are modeled, each with 100 kW, at nodes 11, 23 and 26.
- OLTC turns ratio varying from 0.95 to 1.05 with tap positions constrained by $x_{\max} = 32$.
- Two SCBs, each with a total of 360 kVAR and three switchable units $(N_c = 3)$.
- The figure depicts a loading curve and clear/cloudy PV profiles by the total MW.

System Specifications

The optimization problem is solved every 15 minutes, and multiple scenarios are carried out interchangeably. Equipment-operation penalties are fine-tuned starting with small values to achieve the best coordination with PV VARs.

Table: Cost Coefficients

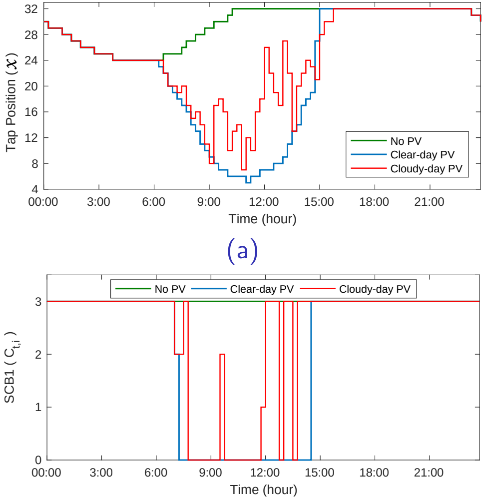
Objective	Symbol	Range	Cost ($)
Loss Reduction	λ_{loss}	-	1
CVR	λ_{cvr}	0.97-1.00 pu	1
Flat Profile	λ_{falt}	0.97-1.03 pu	0.3
Tap Operations	λ_{tap}	0-32 taps	3
SCB Operations	λ_{cap}	0-3 units each	0.1

Case I: Unity power factor and free actions

- $\lambda_{\text{tap}} = \lambda_{\text{cap}} = 0$
- At no PV, the tap actions are moderate and following the load, while SCBs kept supplying full VARs. However, during both clear-day and cloudy-day PV penetrations, the tap-cap actions dramatically increased in frequency to cope with the dynamic net load.

Table: Operation Counts at unity PF of PVs

Equipment	No PV	Clear-day PV	Cloud-day PV
Taps	16	36	43
SCB1	-	3	11
SCB2	-	5	8



(a)

(b)

Figure: (a) Tap positions. (b) SCBs.

Case II: Efficacy of flatness/CVR objectives

- keeping unity PF of PVs and $\lambda_{\text{tap}} = \lambda_{\text{cap}} = 0$
- The capability of the devices is explored to comply with the thresholds of flatness and CVR objectives
- With $(\lambda_{\text{flat}} = \lambda_{\text{cvr}} = 0)$: the devices operate at their maximum bound mostly, increasing voltage variations.
- Considering $\lambda_{\text{flat}}, \lambda_{\text{cvr}}$: the devices closely abide by the flatness objectives. However, increased switching is required.

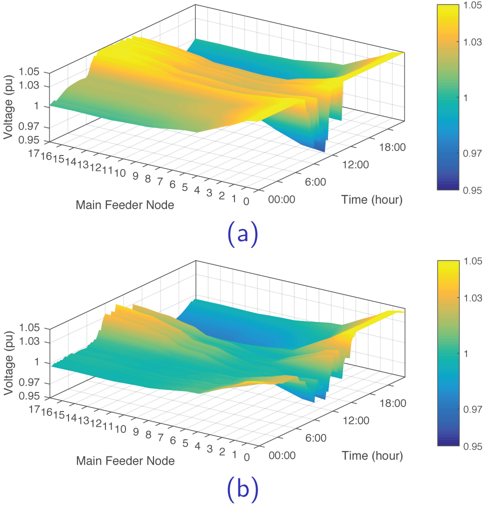


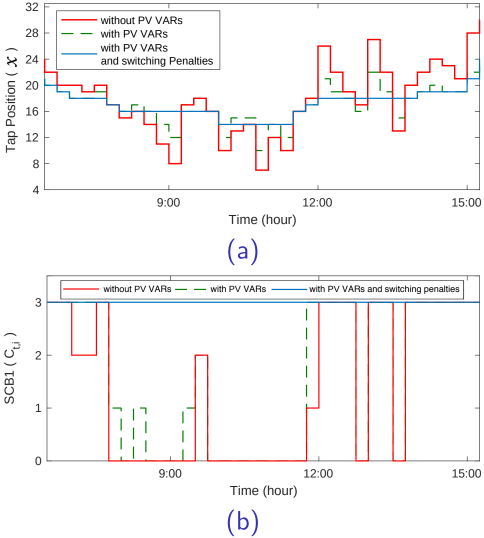
Figure: Main feeder voltage: (a) loss reduction only (b) flatness penalties added.

Case II: OFF-unity PF of PVs

- With $(\lambda_{\text{tap}} = \lambda_{\text{cap}} = 0)$: PVs are not urged to generate/absorb enough VARs.
- As a result, the switching not only maintains a similar behavior, but also increased.
- Considering $\lambda_{\text{tap}}, \lambda_{\text{cap}}$: PV VARs coordinates well with the OLTC taps, while keeping SCB1 unswitched.

Table: Cloudy-day Operations at off-unity PF of PVs

Equipment	With PV VARs	With PV VARs & switching penalties
Taps	47	20
SCB1	12	-
SCB2	-	-



(a)

(b)

Figure: (a) Tap positions. (b) SCBs.

Case II: OFF-unity PF of PVs

The reactive/capacitive PV VARs boost to counteract the peaks and valleys of PV active power. The resulting voltage profiles are further improved

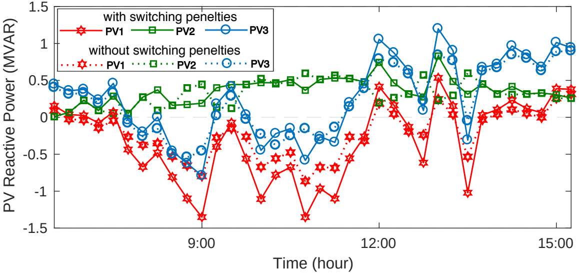
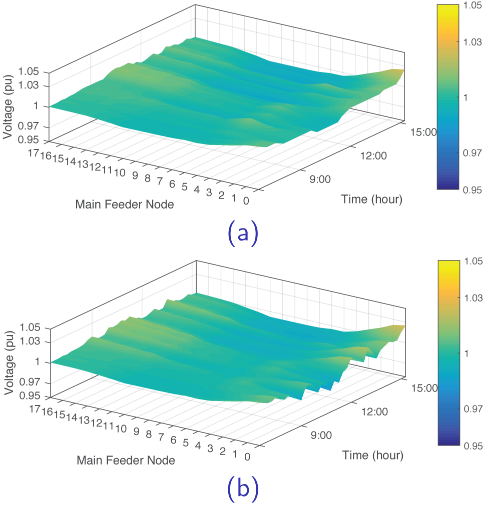


Figure: VARs from each inverter with and without switching penalties.



(a)

(b)

Figure: Compensated voltages (a) with and (b) without switching penalties.

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Exactness of SOCP

The SOCP relaxation is said to be exact if the subtraction both sides of the SOCP inequality constraint satisfies a sufficiently small error.

$$\text{Exactness} = \sum_{t \in T} \sum_{(i,j) \in \mathcal{E}} \left| \ell_{t,ij} - (P_{t,ij}^2 + Q_{t,ij}^2)/v_{t,i} \right| \tag{12}$$

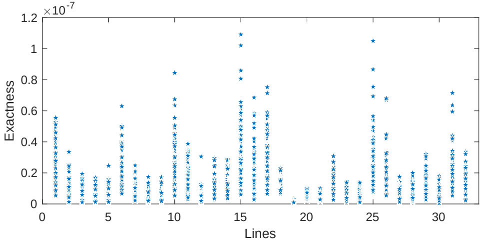

Figure: Exactness of the centralized VVO solution.

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