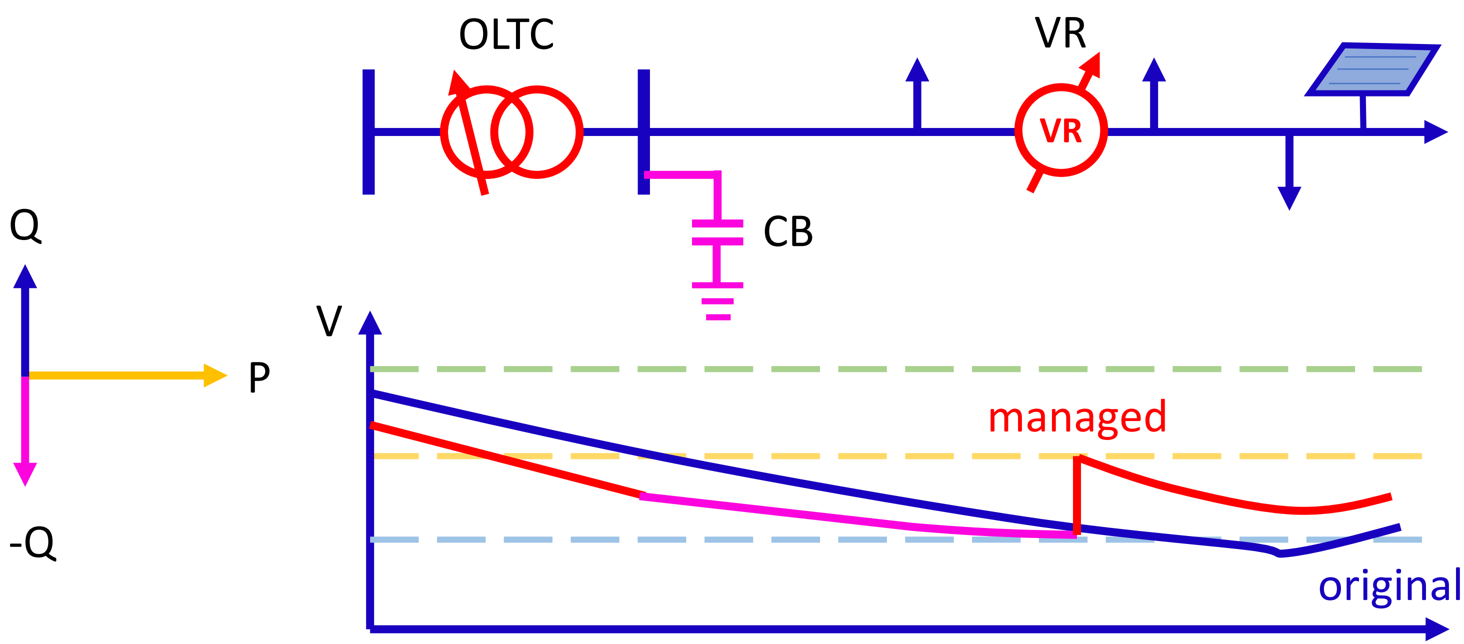
What is Volt-Var Optimization?

- **Volt-Var Optimization (VVO)** optimally manages system **voltage (V)** and **reactive power flow (Q)** to achieve efficient distribution grid operation



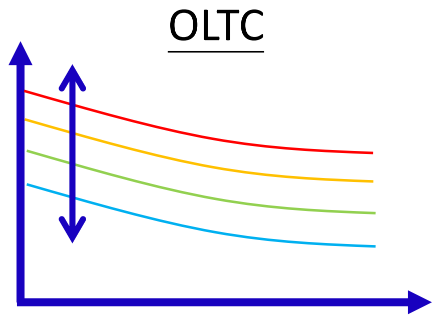
OTLC = On-Load Tap Changer
CB = Capacitor Bank
VR = Voltage Regulator

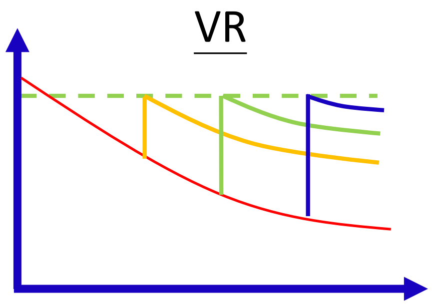
Questions

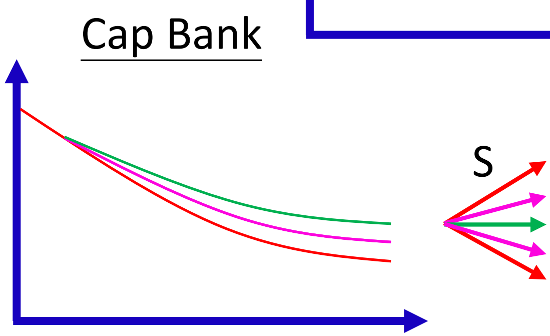
1. What should be OLTC setting? *Why?*
2. Where should VR be placed and how is it operated? *Why?*
3. When should CB be ON? *Why?*
4. What happens after we change these settings?

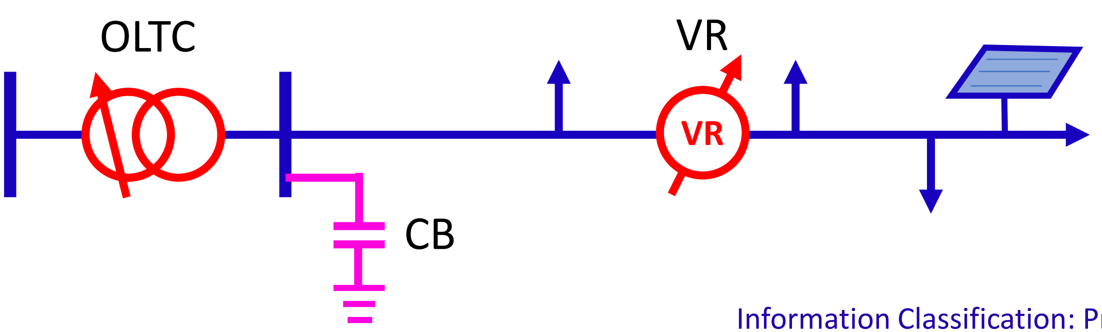
* Concern: Varying Load (Magnitude & Types)

* Size and Location of CB are very important.





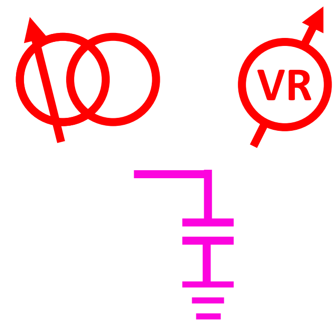




Conservative Voltage Reduction

- Conservative Voltage Reduction (CVR) =

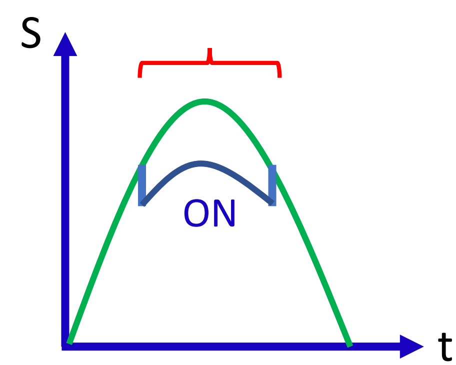
  operating all Volt-Var components
  at *lower* feeder voltage within limit



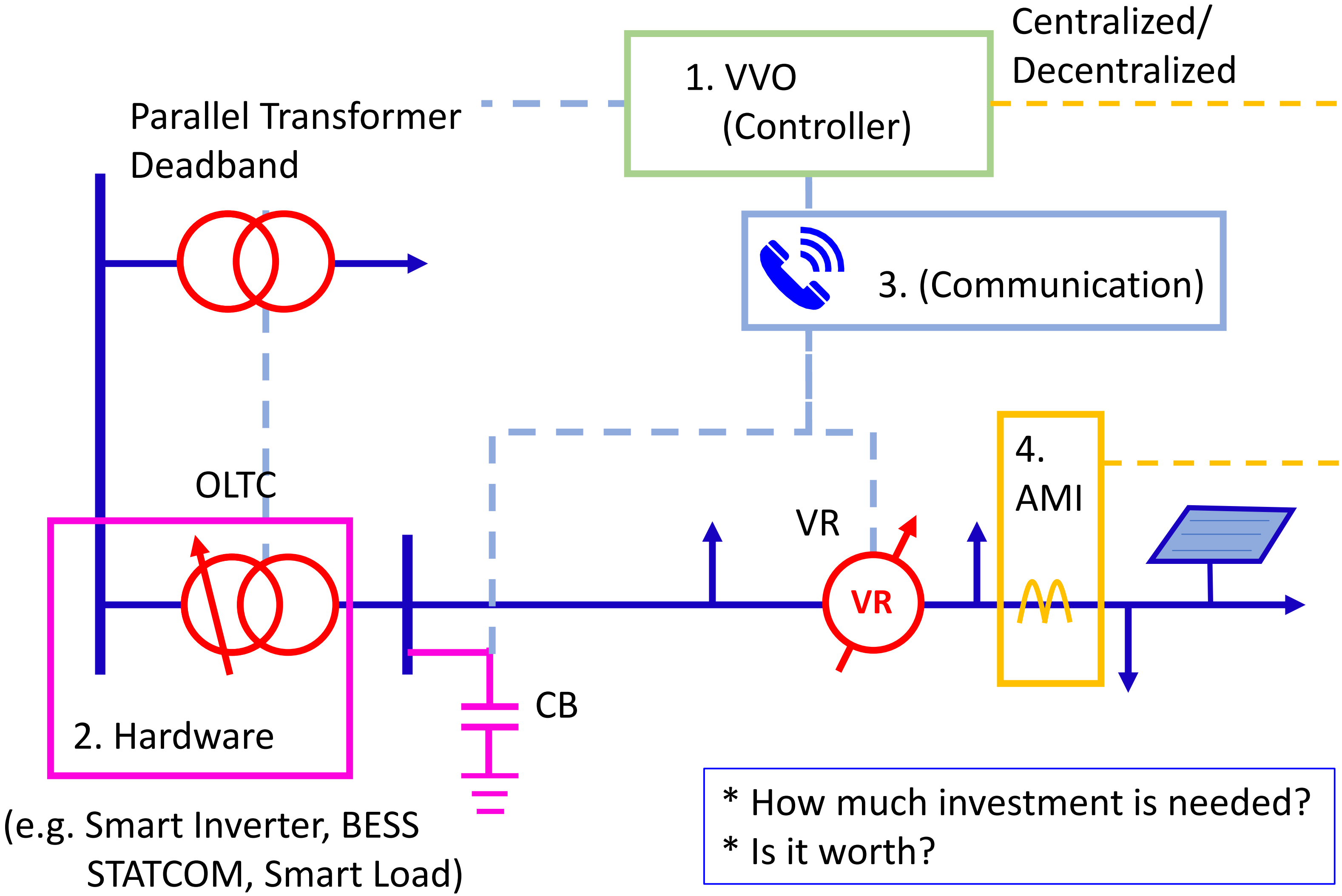
Features:

* Lower system demand also means **less profit**

1. Lower system demand and losses at 0.7% - 1.0% per 1% voltage reduction (e.g. with minimal reactive power losses)
2. Peak Load Reduction
3. Control volt-var components
4. Improved feeder voltage protection
5. Tackle voltage issues with increasing DG
6. Lower Emission



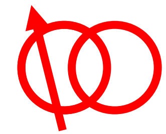
VVO: Required Components



* How much investment is needed?
* Is it worth?

VVO: Required Components

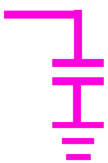
1. LTC: **cost-effective** for circuits with 3 or more feeders
   able to **regulate voltage** with **high load**
   unable to regulate for **unbalance**, single failure affects loads connected

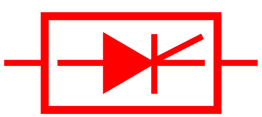


2. VR: choice between single phase VR and three phase VR → OK for **unbalance load**
   can be **maintained** without the impact of transformer
   fault is difficult to detect (under differential zone)
   3 phase VR more expensive than LTC
   cascaded VR can be used

3. Cap bank: provide voltage support and **power factor correction** → effective to reduce losses
   can be controlled by local controllers or SCADA
   create **additional operations** to LTC
   multiple smaller banks are preferred
   can be controlled based on V, I, Q/PF, time, temperature
   cap bank has the right to operate first before regulators

$$V_{rise} = \frac{Q_{var} X_L}{10 V_{KV,L-L}^2}$$





4. Smart Inverters: controlled by fixed PF, V/P, V/Q (mostly for PV)
   hunting and system instability may occur with consumption of var to lower V

Others: STATCOM, SVC, BESS, Dispatchable Loads

VVO: Required Components

Q/V Optimization Application

↓

SCADA Pro System

↓

Two way communication

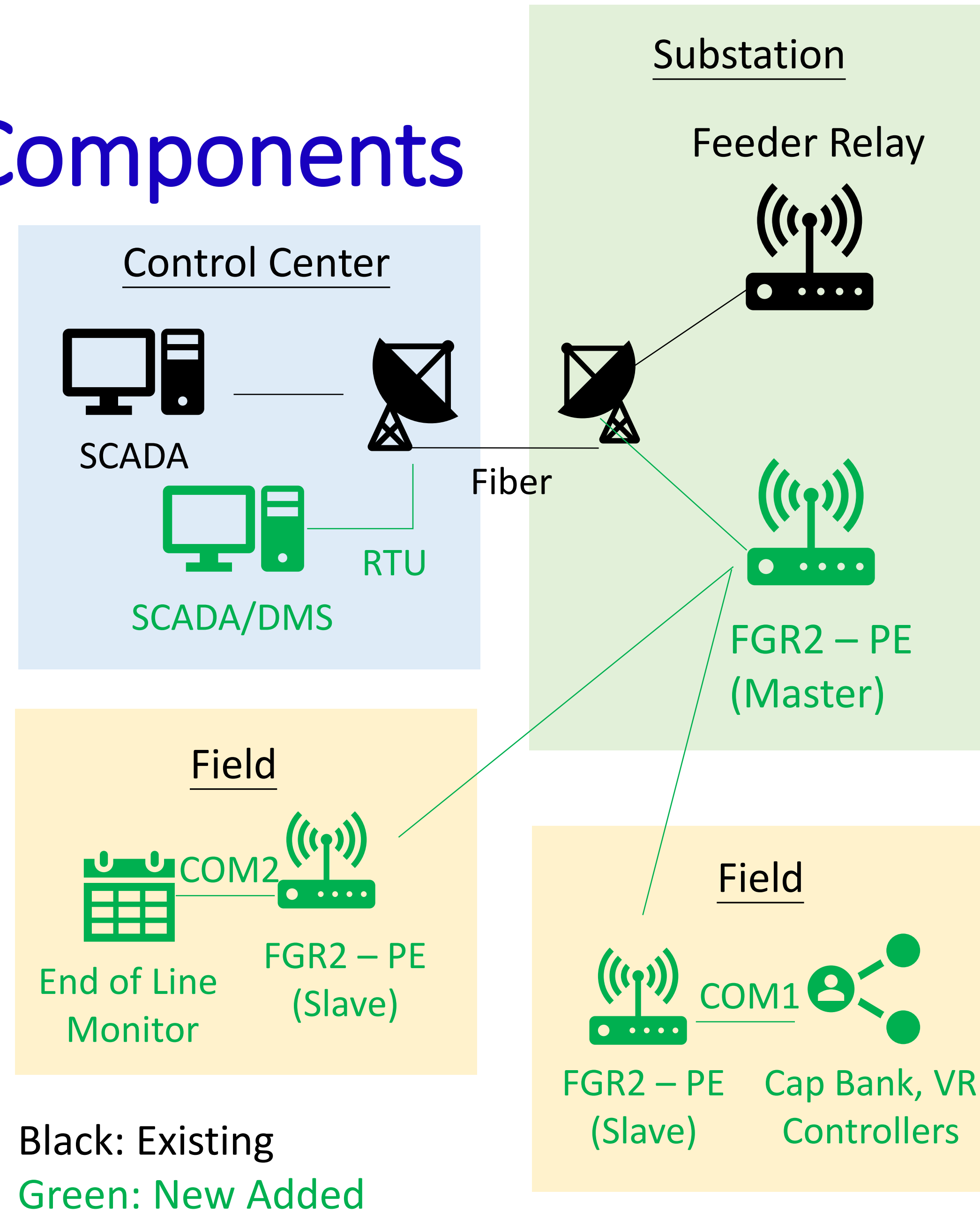
↓ ↓

Sensors | Field Device Controllers

↓

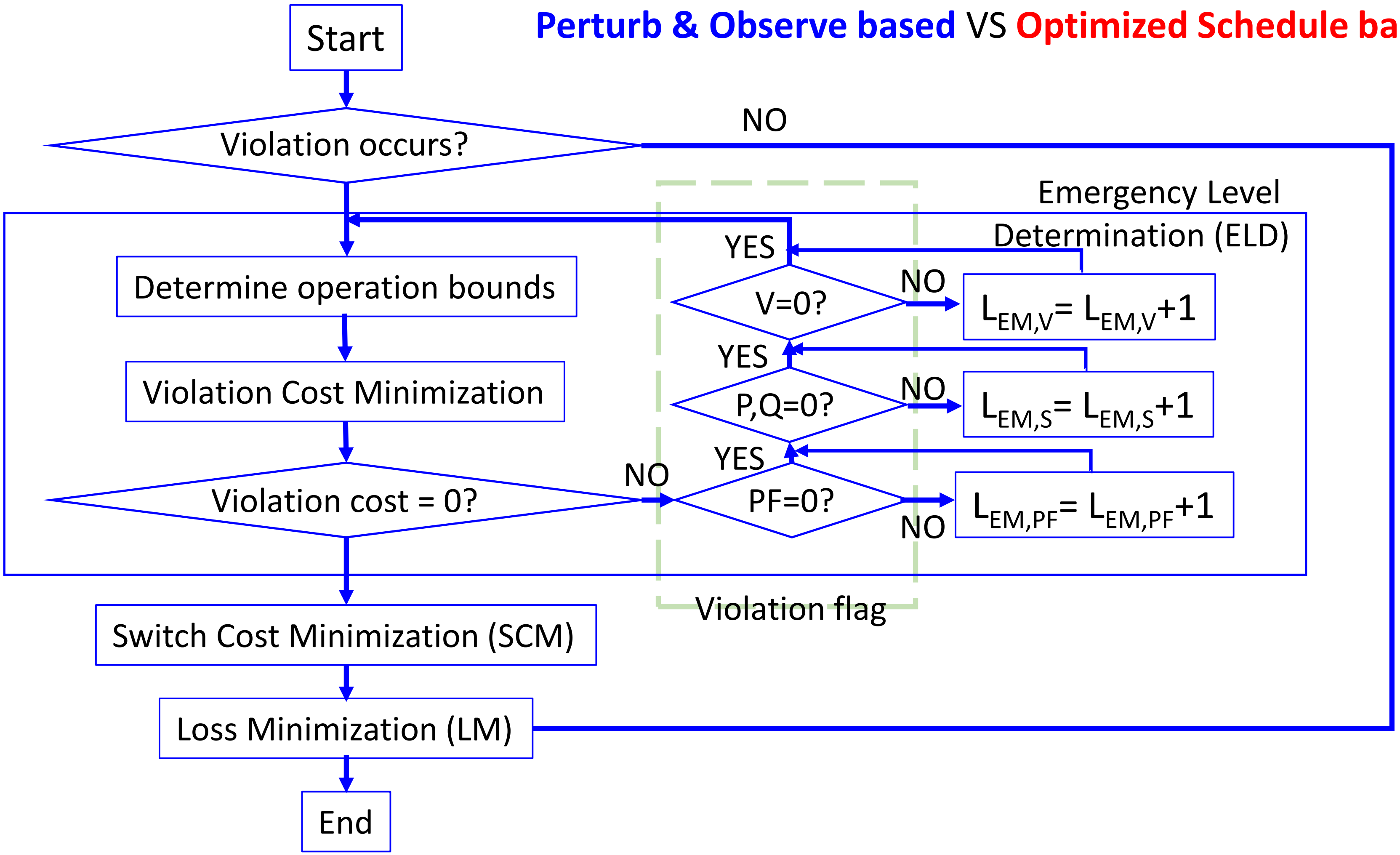
Distributed Network Circuits

1. Filter out strange data itself
2. Make sure all operation in range
3. Decide hierarchical control (who should have say in emergency)

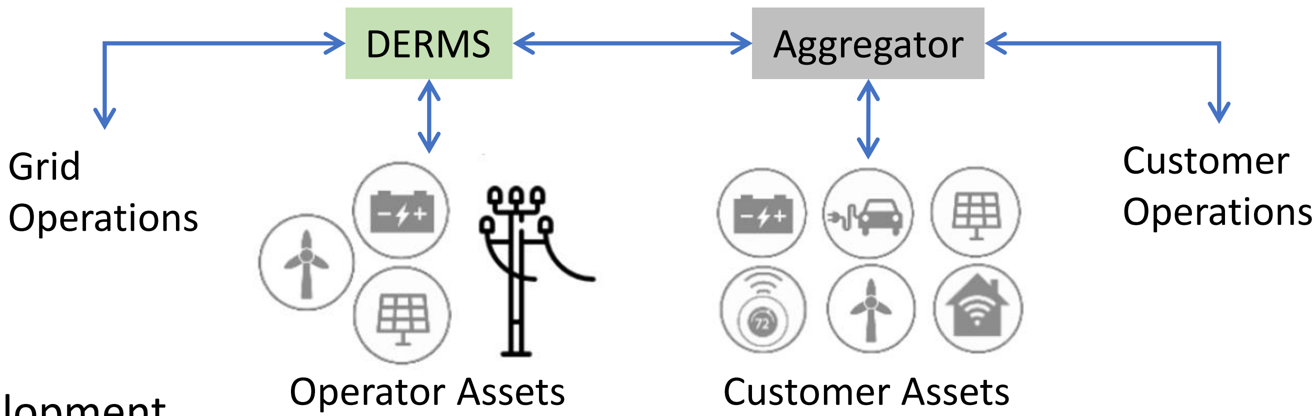


VVO: Actual Control Flowchart

Perturb & Observe based VS **Optimized Schedule based**



VVO: DERMS + Aggregator

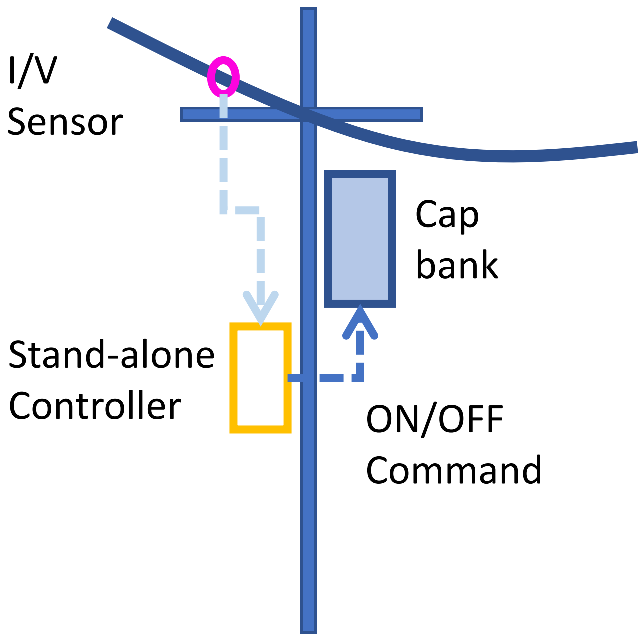


DERMS development

	Modeling	Monitoring & Control	Grid Optimization	Automatic Optimization	Market Integration
Operation	- Modelling - Rule based/ Model based - DER forecasting and reporting	- Monitoring - DER control Validation - Dispatch Manual - Hidden load	- **Volt-Var-Watt Optimization** - Load relief - Forecasting - Dashboards - DER flexibility	- Automatic DER Flexibility - Operating mode - Battery mgmt. - EV as resources - DER protocol	- Market Integration For ancillary services - Market arrangement for constraints mgmt.
Planning	- Enabling Planning apps	- Hosting cap Analysis	- Simulating future DER connection	- Customer connection request	- Boost hosting capacity analysis

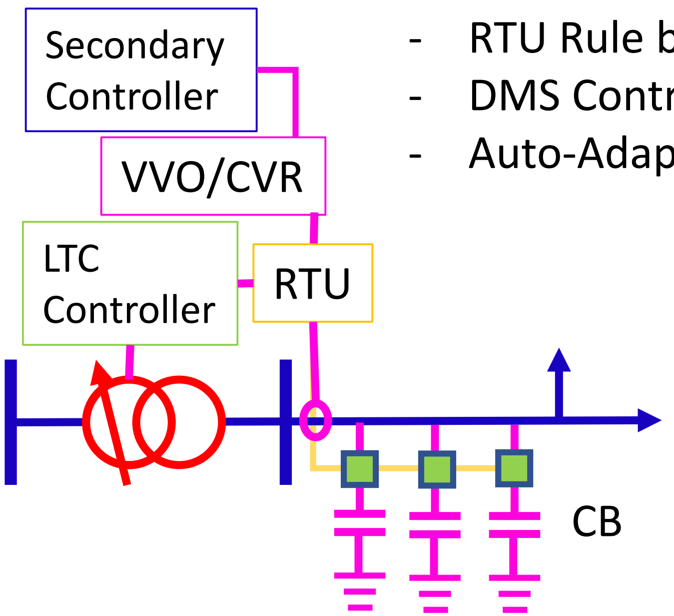
VVO: Supervisory Control OR Stand-alone?

Stand-Alone Control



- Low implementation cost
- No need communication
- No need learning/ coordination
- Not 'optimal' solution to turn ON

Supervisory Control



- RTU Rule based
- DMS Control
- Auto-Adaptive

- High installation cost
- Requires two-way communication
- Learning/ Coordination can be simple
- Improved Efficiency and Possible Optimization

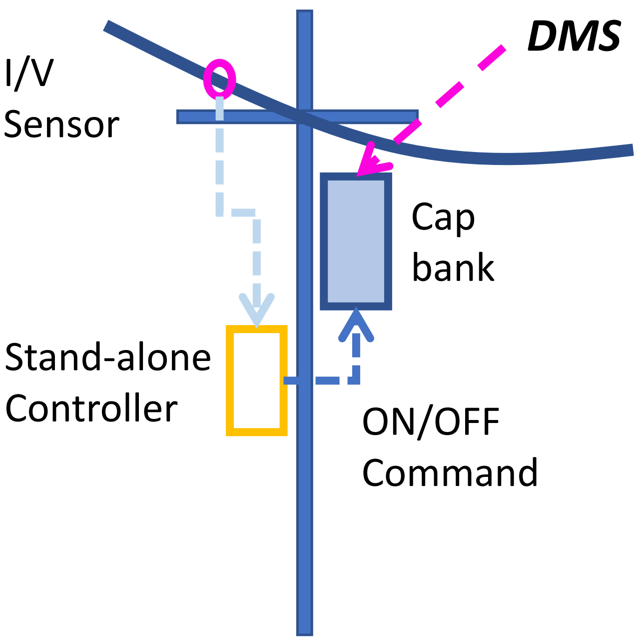
*** How much we should do?**

VVO: Capacitor Placement & Control

Consideration: 1. Where to put? 2. How much to put? 3. How to control?

Distributed Capacitors Controller

1. Independent Phase Switch → Balance the system
2. Zero-crossing switching → Avoid current spike (Zero-voltage switch ON, Zero-current switch OFF)
3. Monitor Power Quality and Detect Fault
4. Shunt cap to absorb harmonics, increase capacity
5. Possible telecom interference



Integrated Distribution Management System

1. Improved efficiency, grid performance, demand management, visibility and data for decisions
2. 2/3 losses in distribution → minimize loss (esp. for valley and peak condition)
3. Virtual Power Plant & Demand Response Applications

VVO: Foreign Initiatives and Results

Table 1: Foreign Initiatives and Results

Snohomish County PUD	Investment: **$5 million** (26% Communication; 44% Capacitor; 10% VR; 20% DMS) Energy Saving **= 53,856MWh/yr**, Reduced Losses **= 11,226MWh/yr** Typical Feeder: 1.61% energy saving (198MWh/yr) **** Smart Grid Investment Grant: $1.5 millions*** Equipment needed: Line Drop Compensator, Voltage Regulator, Capacitors, System Metering, Reconductoring, Advanced Modelling Tools, Communication Network Sensors Benefits: Reduced Load and Line Losses; Improved Reliability; Substation Automation; Reduced Maintenance Costs
Northwest Energy Efficient Alliance	**2.5%** voltage reduction → **2.07%** energy saving without impact on consumer power quality
Oklahoma Gas & Electric	42 Feeders with 2.06% (>2% as target)/ 8MW peak load reduction Goals: Expand to 300 Feeders with 74MW reduction

Conservative Voltage Reduction factor (CVRf)

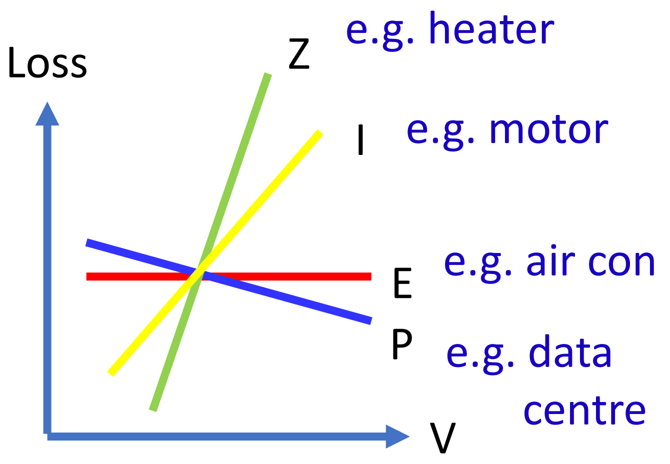
$$\boxed{CVRf = \frac{\Delta P}{\Delta V}}$$

amount of power reduction per 1% voltage reduction (0.7% - 1%)

Table 2: CVRf on Paper	
Utility/Paper	CVRf
Dominion Virginia Power	0.92%
Northwest Energy Efficient Alliance	0.78%
Snohomish County PUD	0.62%
Hydro Quebec.	0.55%
PECO	0.50%

Observations:
CVRf is **season** & **load-dependent**.

Losses – Voltage Characteristics



**** Don't Implement CVR/VVO at Data centre → More Losses***

VVO: Formulation

*** Run Power Flow Simulation to compare VVO On and OFF difference → benefit**

$$P_{optimal} = f(V, I, OLTC, CB, VR, P_{DG}, Q_{DG}, P_L, Q_L)$$

Voltage Constraint:	$V_{MIN} \le V \le V_{MAX}$	(by law)
Current Constraint:	$I_{MIN} \le I \le I_{MAX}$	(thermal constraint)
Apparent Power Constraint:	$S_{MIN} \le S \le S_{MAX}$	(transformer saturation)
Power Factor Constraint:	$PF_{MIN} \le PF \le PF_{MAX}$	(by law)

Objective Function:

$$J = \underbrace{\sum_{i=1}^{24} \mu_{\Delta V_{2_i}} + \sum_{i=1}^{24} \mu_{pf_i}}_{\text{Make sure voltage and PF are close to set point}} + \underbrace{\mu_{N_{tap}} + \mu_{N_C}}_{\text{Minimize no. of tap change/CB ON Off}}$$

1. **Load forecasting** and **Power Flow analysis** are needed to find **optimal schedule**.
2. **Real time coordination** with master controller is needed.
3. **System Reliability** is improved as Volt-Var components react to events in grid.

VVO: Necessity in Load Modelling

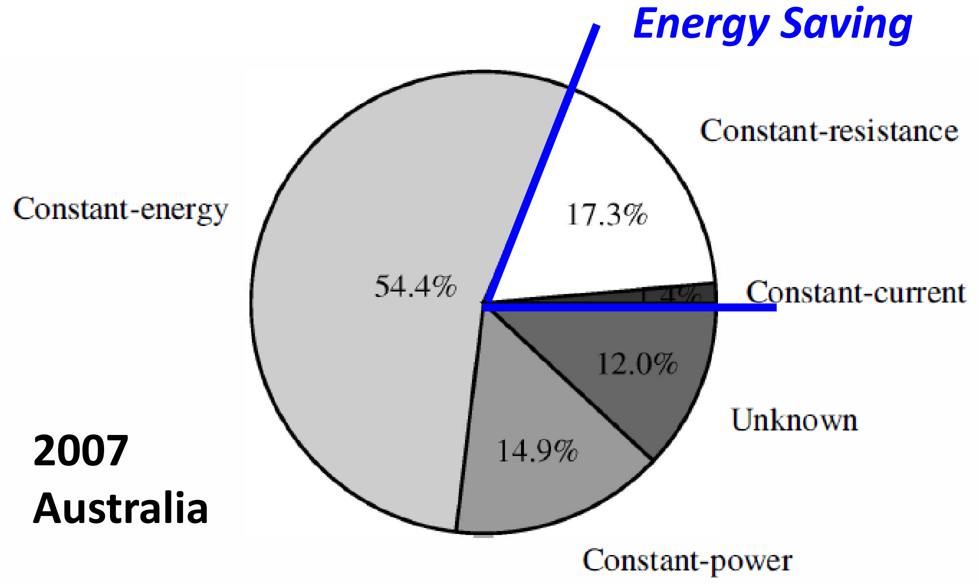
Load Modeling provides information on **potential in CVR** and **influences of voltage to load**. (But it is time-dependent)

- Three types of load modelling: Curve Fitting (e.g. ZIP load), Physical Components (e.g. Lighting, Air Conditioning in Residential/Industrial), AI-based (Recurrent NN)

Motors:
Both high/ low voltage takes more current, and leads to overheat.

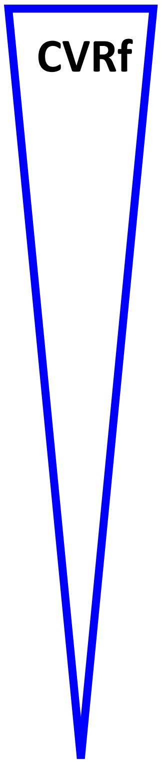
Curve fitting is **easy to do**, but it is changing in time. Physical components are more preferred as it is **behavioral based**, but it requires **client information**. AI-based shows **best result**, but it takes large **computation effort**.

2007 Australia



%saving = 2 x %voltage reduction x % Z load

VVO: CVRf to load type and Thermal Cycle

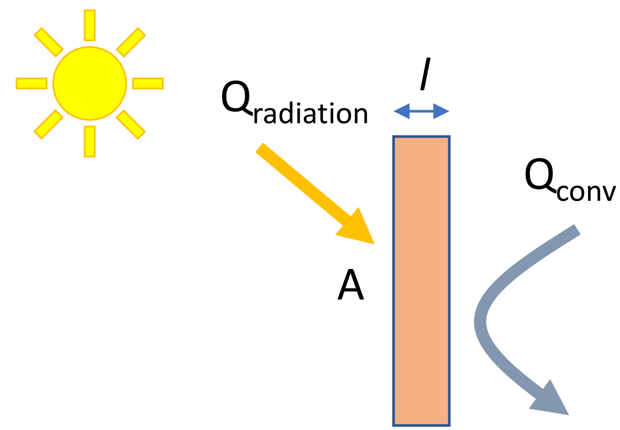


CVRf	Equipment Type
1.9	Fans, Air handler, FCU
1.7	Pumps
1.5	Halogen Lighting
1.0	Self Contained Air Con
0.8	Refrigeration Compressor
0.6	Fluorescent Light (Magnetic)
0.5	Small Chillers, Heat Pumps
0.3	CFL, Fluorescent (Electronics)
0.2	Computer, TVs, LED

*** Average CVRf ~ 0.7% – 1%**

Thermal Cycle in Air Conditioning

1. **More on feedback control**
   → lower V = need a longer time to cool down the room = same energy overall
2. **More complex calculation**

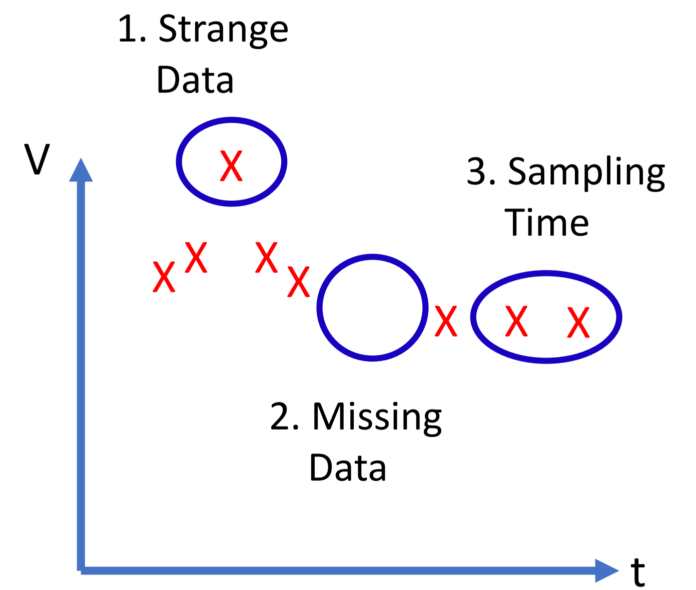


(a) Thermal storage
(b) Varying outdoor and indoor situation

VVO = Data Driven Decision

Load is ***fluctuating*** in nature.

How close sensors should be put in feeder?



Data is detected as fluctuating.
Possibility: 1. It is really fluctuating (99%)?
2. It is a wrong data (1%)?
Decision based on wrong data is **dangerous**!

Everything in blind are estimated with model

<u>Method 1: Resampling</u>

* Data should **sample more frequent** at time load fluctuates much/ load at peak demand

<u>Method 2: Modelling to check/replace data</u>

* e.g. EPRI Green Circuit: $kW = \underbrace{K_1 (KW_{avg}) + K_2 (V)}$

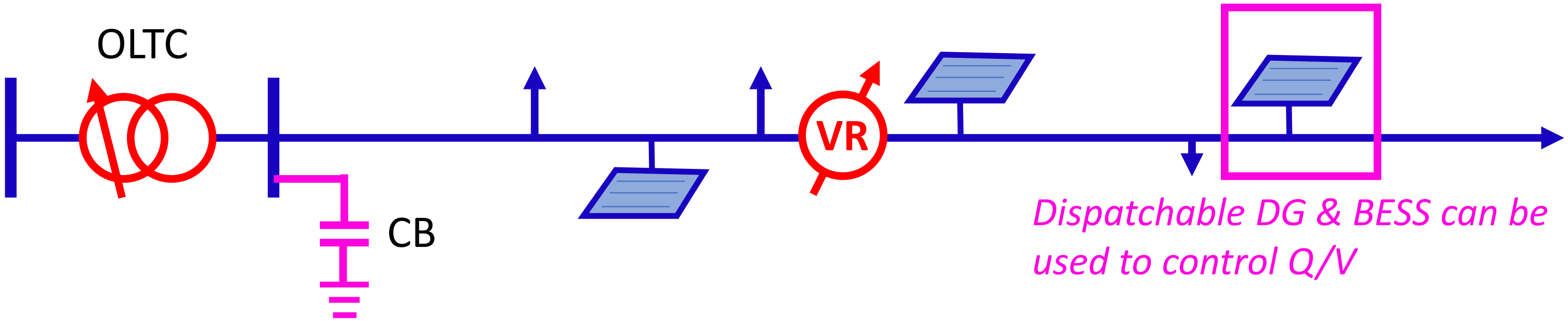
which is basically **ZIP load**: $P(V) = K_P + K_I(V) + K_Z(V^2)$

* It helps smoothening out data. Applying delay to decision also works.

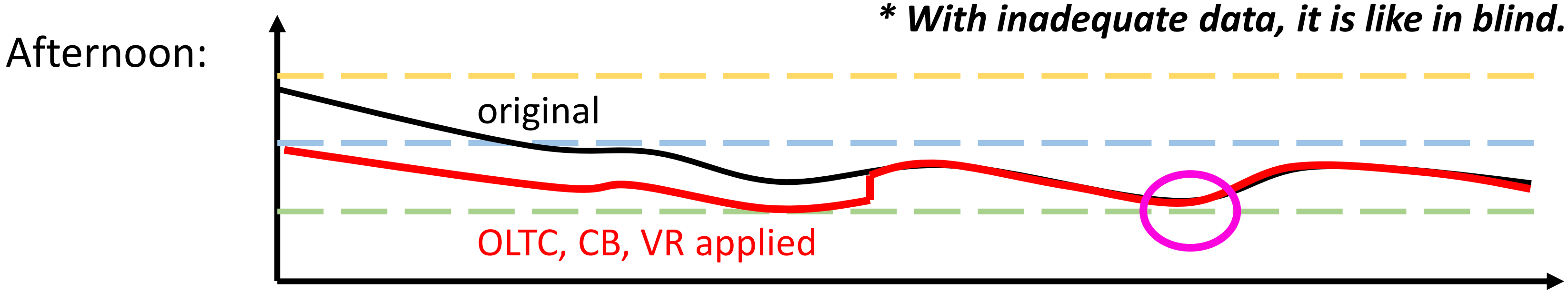
VVO: Technical Challenges

- Distribution State Estimation: Load information, DG and Power Flow are essential to VVO decision.
- Computational Burden: Optimization Problem and Load Forecasting are difficult and time consuming to solve.
- Complex Network Analysis: Unbalanced system, meshed system with DG, Hierarchical control are in application.
- Practical Consideration: Parallel transformer control, voltage collapse ride-through, load variation – what to do?
- Data Analytics: AMI receives intensive amount of data with computation where to store and what should be the sampling time?
- Reported Problems: Transformer Saturation (with only AMI)

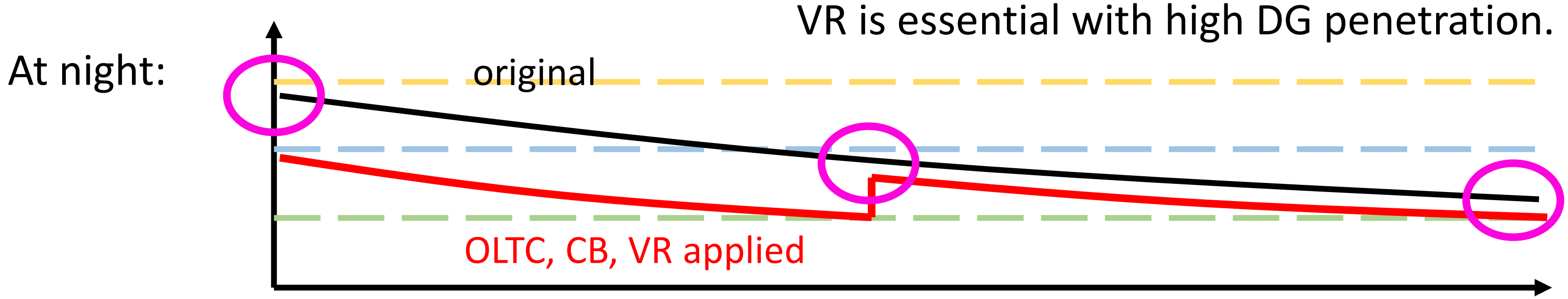
VVO: Increasing DG Penetration



***** With inadequate data, it is like in blind.***



VR is essential with high DG penetration.



*** Data at feeder start and end, VR, load and DG are needed.**

SWOT Analysis for VVO

Strength:
- Large network = high potential for energy and losses reduction
- With prior knowledge to operate cap bank/ LTC/ VR

Opportunity:
- Increasing AMI
- Increasing DG connected
- Initiatives in Demand Response/ Loss Reduction
- Less demand
  = delayed replacement/ additional components

Weakness:
- no subsidies to construct the infrastructure → costs
- takes time to understand the mechanism → reliability?

Threat:
- More new control & components
  = More uncertainty
- Data Leakage / Data Integrity
  → power system control is safe?
- Voltage is lowered than expected (Violate the rule)

Decision Making for Voltage Optimization?

Energy Consumption & Cost
Load Profiles & Equipment Utilization
Voltage Oversupply/Tolerance
Load Type & Potential Cost Saving
* Any Alternatives?

Site
Service/Product Supplier
Warranty & Regulations

Understand → Evaluate → Assess Feasibility → Procure → Implement

Business Drivers
Network Plan Strategies
Energy Management
Potential Risks on Power Quality
Known issues on Infrastructure
Enough Information on Equipment?

Total Cost of Ownership (TCO)
Technical Consideration
Operation & Maintenance
Alternatives to each components
Risk Management
Pre-Implementation Assessment

Pre/Post
Installation
Roles/
Responsibility?

1. What is the cost benefit?
2. How much to do/aim at?