Mid-Term Presentation of

Consultancy Services of the review of Conservation Voltage Regulation (CVR) and its applicability to the CLP Power Grid

Stage 1

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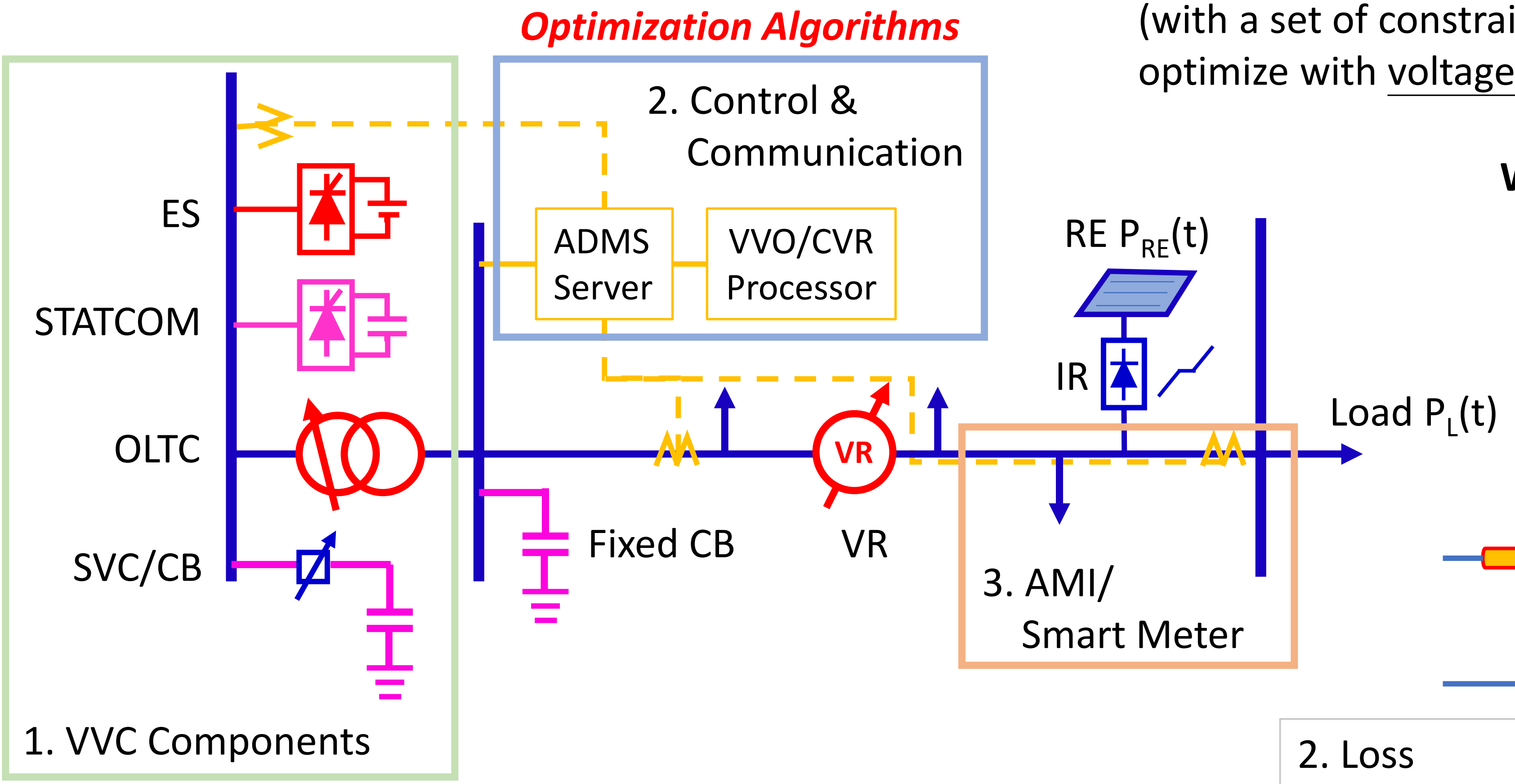
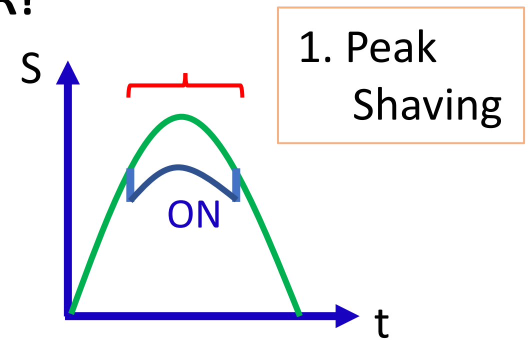
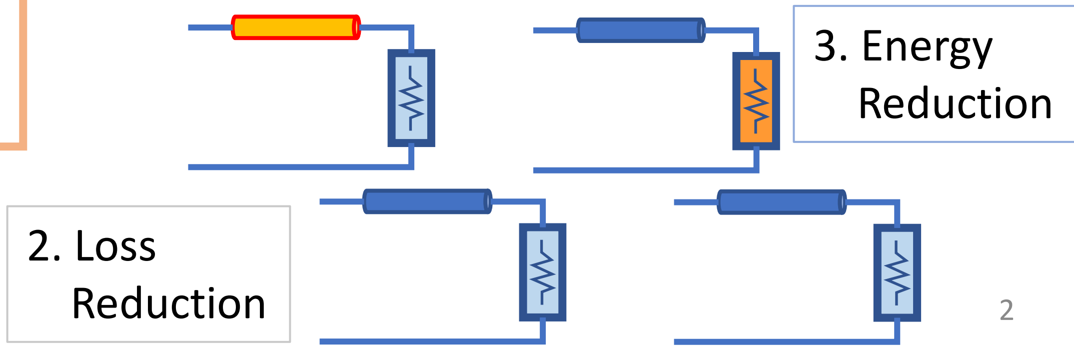
Volt-Var Optimization (VVO) VS Conservative Voltage Reduction (CVR)



VVO is to optimize the control of **Volt**-**Var** Components. (with a set of constraints/objective function) & **CVR** is to optimize with voltage reduction. Without affecting equipment performance

Why CVR?



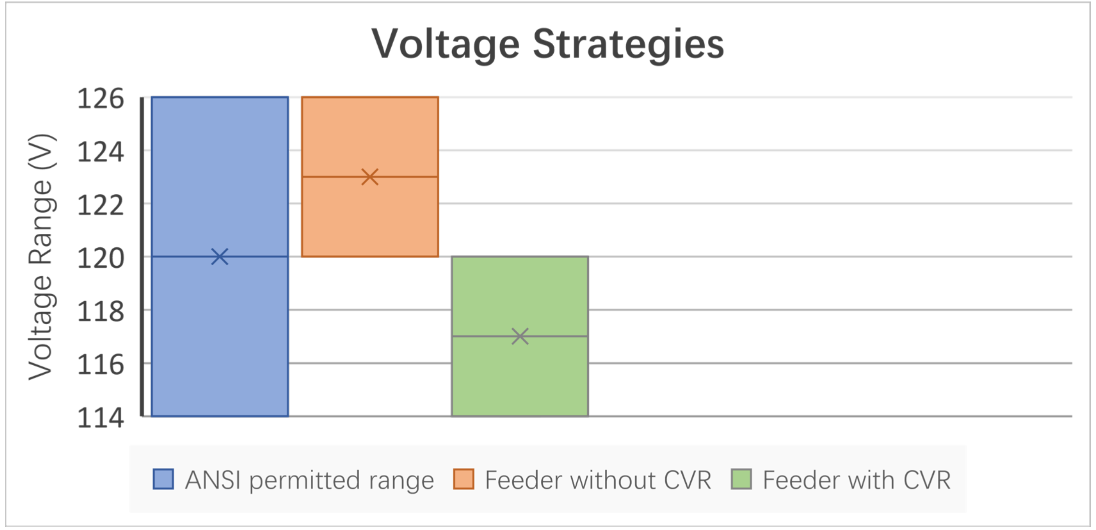


Why CVR ?

Promote Energy Efficiency
Embrace Energy Saving
as does **in other utilities**

National Service Voltage Standard (ANSI C84.1)

- Normal Conditions: **114V-126V**, allows ±5% service voltage bandwidth
- All **electric devices operate properly** → Should not receive any complaints



CVR →

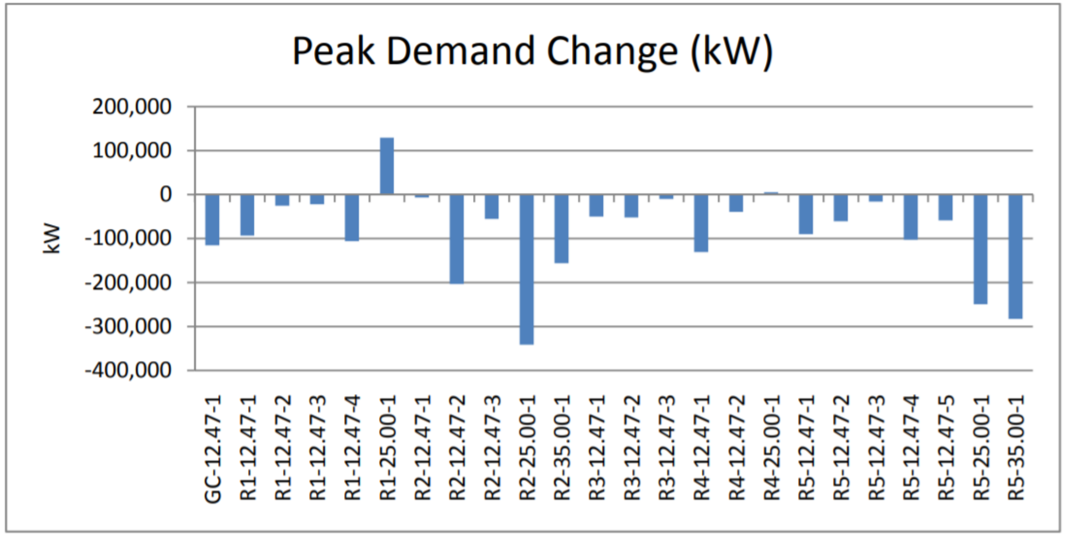
- Peak Load Reduction
- Annual Energy Reduction
- Loss Reduction

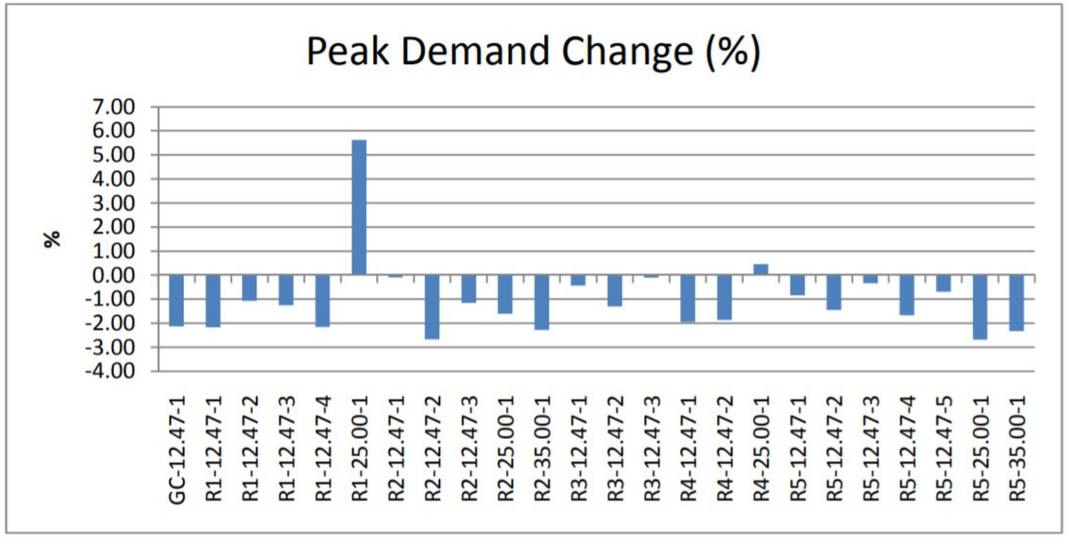
Compared with other VVC schemes, CVR is a more cost effective and more reliable way to achieve these effects.

* Based on the test data from NEEA, PNNL and NRECA.

Why CVR ?

- Peak Demand Reduction





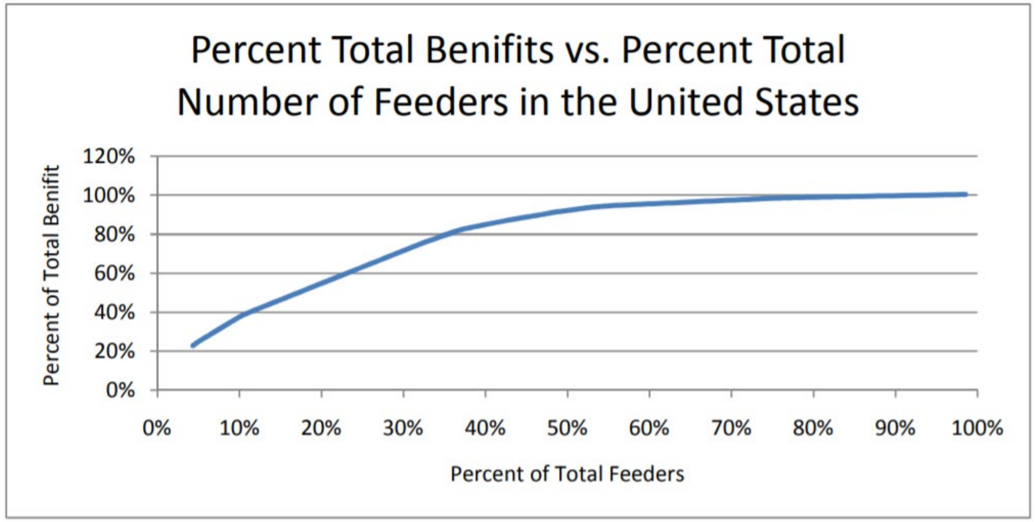
CVR provides **peak load reduction** and **annual energy reduction** of approximately 0.5%-4% depending on the specific feeder.

Useful to tackle high electricity demand in extreme weather

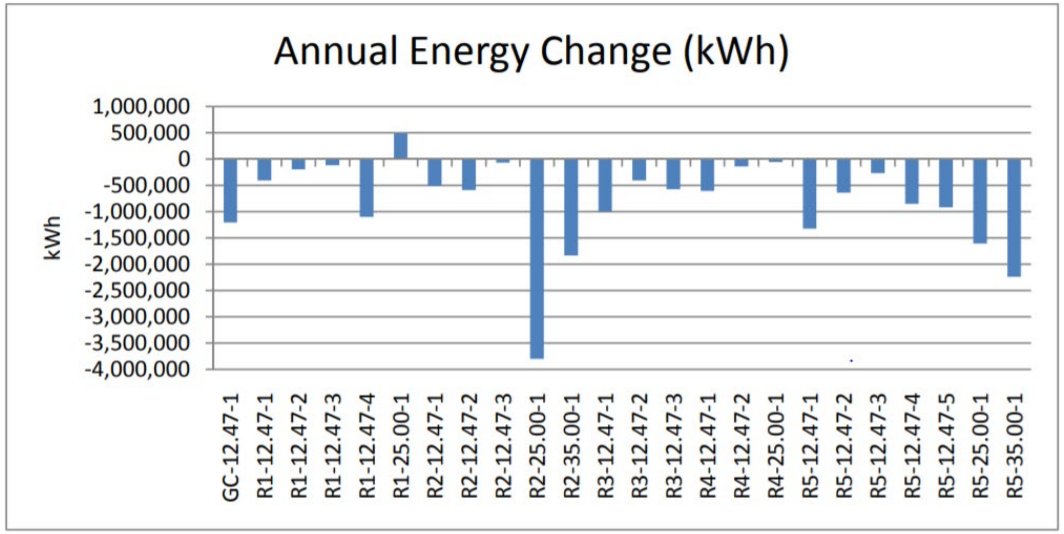
* Based on the research data from PNNL in USA. The x-axis presents different test areas.

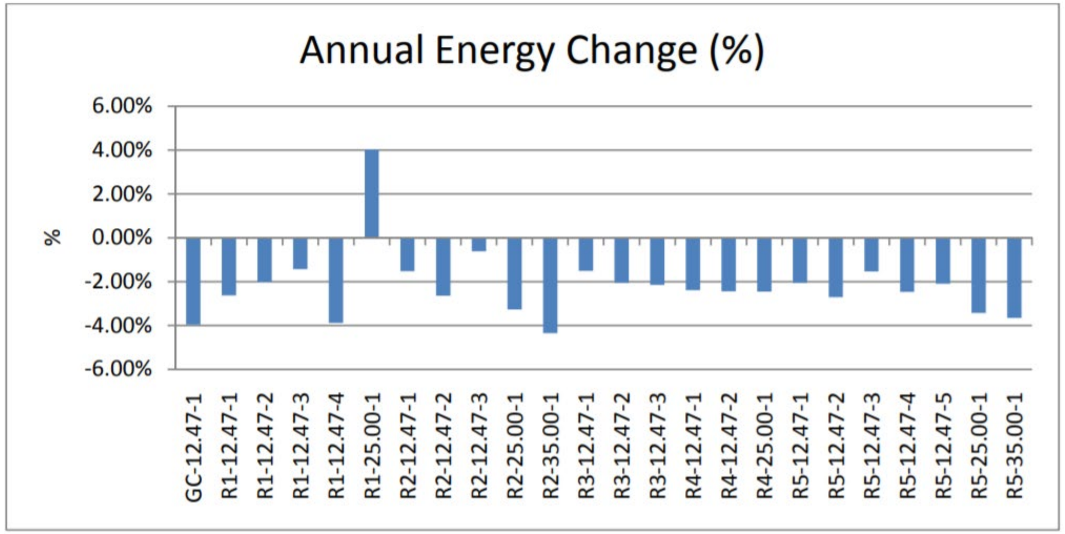
Why CVR ?

- Annual Energy Reduction



100% deployment of CVR provides a **3.04%** reduction in annual energy consumption. **40%** of distribution feeders, the annual energy consumption is still reduced by **2.4%**.



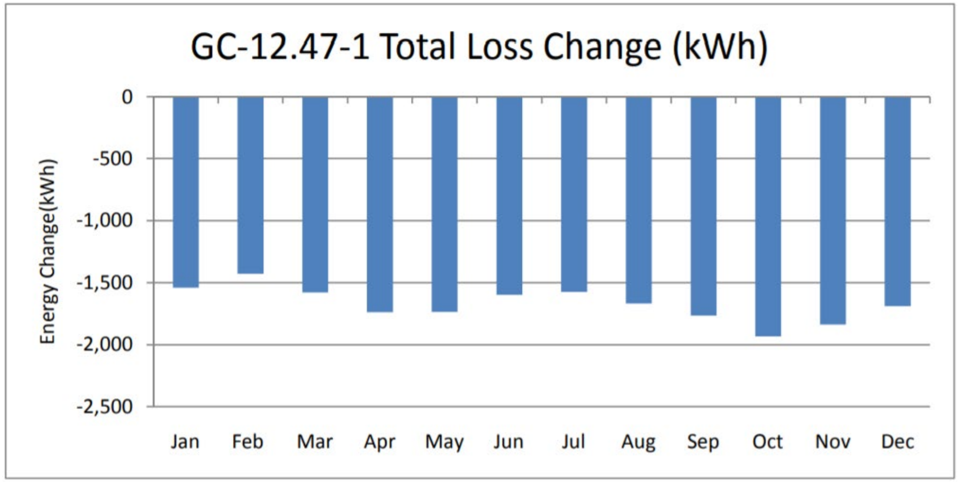


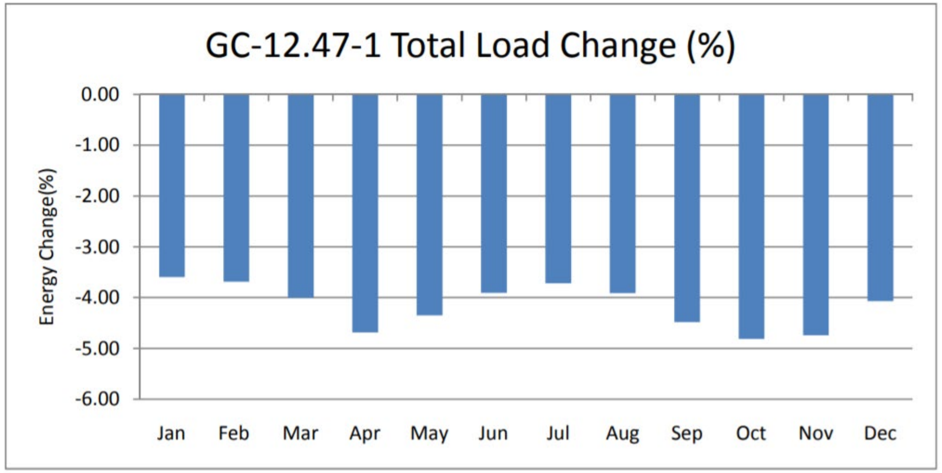
CVR has the potential to **reduce annual energy** on distribution feeders. The ability to reduce the annual energy of a feeder could be further increased through upgrades such as feeder **reconductoring** and installation of downstream **voltage regulators (VR)**.

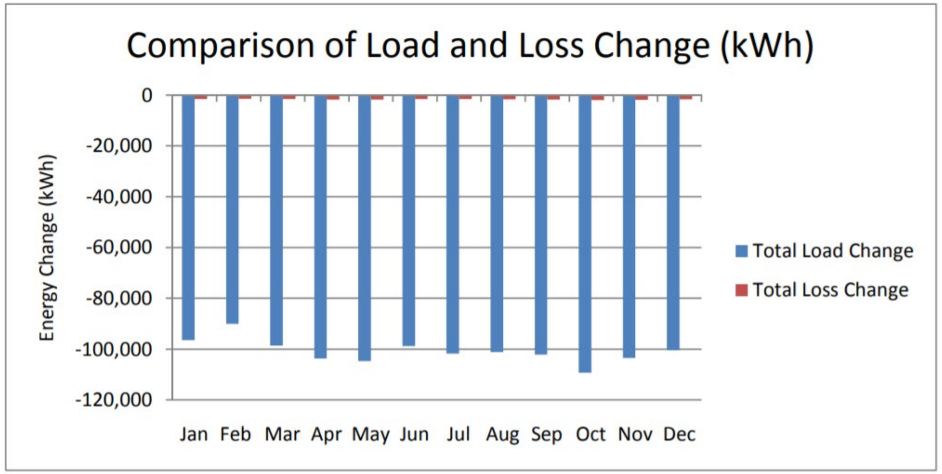
* Based on the research data from PNNL in USA. The x-axis presents different test areas.

Why CVR ?

- Loss Reduction







(major)

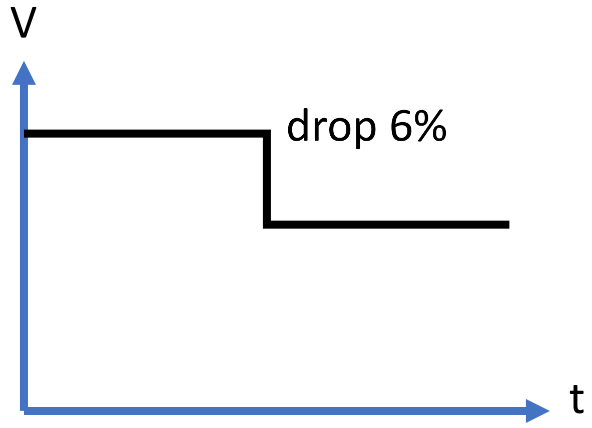
When CVR is in operation, **98%-99%** of the energy reduction occurs in the **end use loads**, while **1%-2%** of the reduction in energy consumed can be attributed to **losses**. **Loss reduction** is **a side effect** of CVR. (minor)

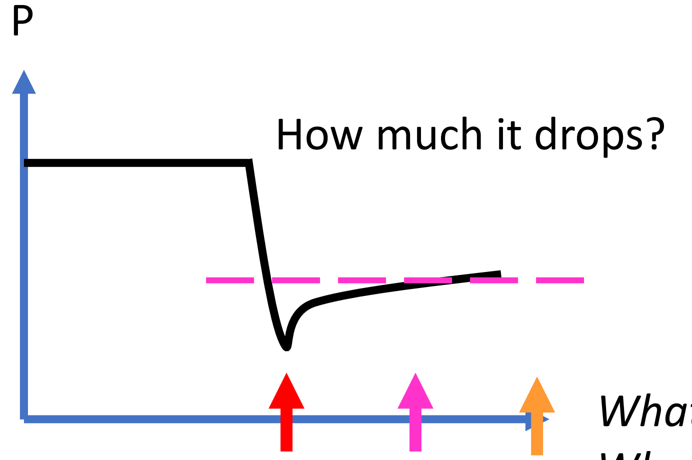
* Based on the research data from PNNL in USA.

Why CVR ? List of Adequate Researches and Application Experience

Year	Region	Utility	Method	Feeder	Result
1980s	Indiana, USA	American Electronic Power System (AEP)	**Field Trial**	**Residential** (R) Industrial (I) **Commercial** (C)	**0.5%-0.8% load reduction** per 1% voltage reduction
1990s	Vancouver Island, USA	B.C. Hydro	**Field Trial**	R,C	**0.51%-0.78 % load reduction** per 1% voltage reduction
……	……	……	**……**	……	……
2005	Canada	Hydro-Quebec System	**Field Trial**	R,I,C	**0.4% energy saving** for 1% voltage reduction
2010	USA	Pacific Northwest National Laboratory (PNNL)	Simulation	R,I,C	peak load reduction and annual **energy reduction** of **0.5%-4%**
2014	Columbia/Kentucky/Iowa, USA	National Rural Electric Cooperative Association (NRECA)	Field Trial Simulation	R,I,C	Simple **paybacks** for CVR projects are generally in the 0–2 year range
2015	Virginia, USA	U.S. Department of Defense	Simulation	R,I,C	Demonstrates 8% to 10% savings based on the **combined technology**

CVR factor – How to quantify the effectiveness?





What to measure?
When to measure?

1. $\boxed{\mathrm{CVRf} = \dfrac{\Delta P}{\Delta V}}$ How much (percentage of) **power** drops when voltage is dropped by 1%?

What does power mean? What power we measure?

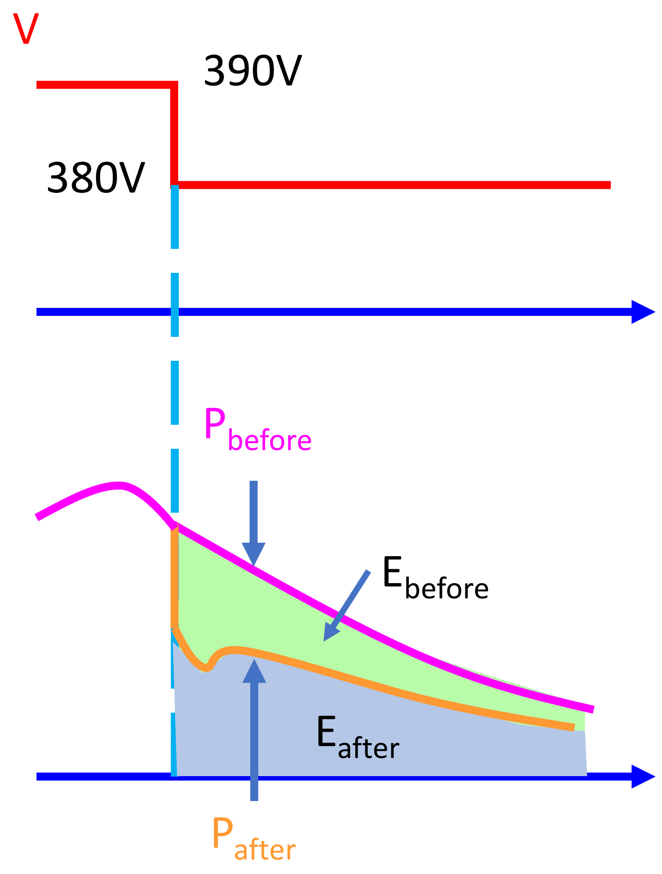
2. $\boxed{\mathrm{CVRf} = \dfrac{\Delta E}{\Delta V}}$ How much (percentage of) **energy** drops when voltage is dropped by 1%

We perform energy reduction. We take average!

3. $\boxed{\mathrm{CVRf} = \dfrac{\Delta \mathrm{P}_{\mathrm{loss}}}{\Delta V}}$ How much (percentage of) **power loss** drops when voltage is dropped by 1%

We perform loss reduction.

CVR factor – How to quantify the effectiveness?



Which **CVR factor** should be used?

1. **dP/dV** value depends mostly on **when to measure**.
2. **dE/dV** value requires **accumulating power used over time**.
3. As **energy reduction** is the focus of this study, **dE/dV** will be used as CVR factor tested.
4. (Method 1) To avoid transient effect and constant energy load, P_{after} can be **measured in long enough time (e.g. 1 hour)** after voltage reduction.
   (Method 2) Keep track all voltage, current and PF points within the period (e.g. 1 hour), **sum up** the real power to calculate dE/dV.

CVR factor – How to quantify the effectiveness?

- NEEA's case:

Pilot Demonstrations – 2.5 years

✓ 10 Distribution Substations with 30,000 customer involved
✓ Average Voltage Reduction = 3.03V (2.5%)
✓ Average Energy Saved = 2.07%
✓ kWh CVRf = 0.69
✓ kW CVRf = 0.78

sum up over year

take average over peak reduction

- Record *hourly average* for a week pre- and week post voltage, kW and kVAR
- Goals: Estimate end-user energy saving due to voltage reduction
  - Savings only meant to be 'an average'
  - Loss saving is calculated separately.

- SMUD's case:

CVR program is applied in 2014

✓ 14 Distribution Substation with over 118 Feeders (18% of SMUD feeder)
✓ CVR factor (kWh) ranged from 0.3 to 0.9, averaged at 0.6.
✓ 36,520MWh/yr was saved. (0.3%)
✓ kW CVRf (trial) is around 0.5 – 1.25

- Overcompensation of reactive power is observed as a reason to increase line losses after CVR scheme.
- Statistical Model was built:
  - 1.8% average voltage reduction = 2% MWh & 1.1% MW reduction

CVR factor – How to quantify the effectiveness?

- Snohomish County PUD's case:

Installed CVR from 1992 to 2006

✓ 68 Distribution Substations with 290,000 customer involved
✓ Average Voltage Reduction = 2.75V (2.3%)
✓ Average Energy Saved = 53,856MWh/Yr
✓ Reduced Losses = 11,226MWh/Yr
✓ kWh CVRf = 0.7

- With Voltage Regulators, Reconductoring, LDC, and Advanced Modeling
- Improved voltage quality (less voltage swing) with no low voltage *complaints*
- Average customer saved = 1.32%
- Project Sum = $31M USD (with half Federal share)

- OG&E's (IVVC) case:

CVR program is applied in 2011

✓ Nearly 400 feeders by 2017
✓ Peak Demand Reduction (MW) = 74MW
✓ kWh CVRf = 0.5 – 1.0 (average = 0.7 summer)
✓ Energy Reduction = 1986 MWh (sum)
Line Loss Reduction = 82.8 MWh (sum)

- kWh CVRf:
  0.76% for residential loads
  0.99% for commercial loads
  0.41% for industrial loads
- Two-stage control:
  Reactive Power Compensation → Voltage Reduction

CVR factor – How to quantify the effectiveness?

- EPRI's case:

Installed CVR from 1992 to 2006

- ✓ 42 Distribution Circuits were modelled
- ✓ 2.34% Energy Reduction
- ✓ kW CVR = 0.77 (summer), 0.33 (winter)
- ✓ Average Line Loss Reduction = 17% per circuit

- Main saving is from phase balancing & reactive power compensation
- High Load Density is one reason to have bad result.
- Expected benefits decline with more electronic loads and adjustable speed drives

- BC Hydro's case:

CVR program is applied 5 years from 1996

- Winter: Energy Reduction = 1.3 GWh/yr
  inc. 2 years with 1.8GWh/yr
- Peak Demand Reduction = 1.6MW (1.1%)
- 2007: installed system with 7 GWh (1%) saving
- 2020: 300GWh/yr with 65 substation in VVO

Goal: flattening voltage profile & lowering voltage

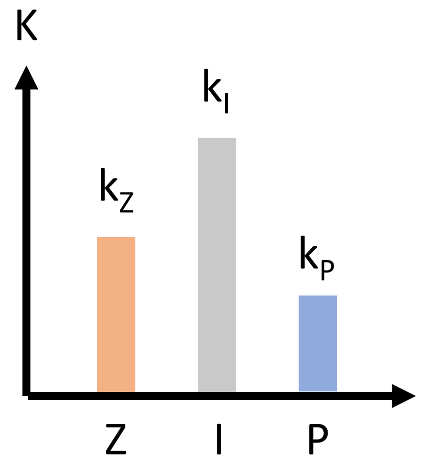
Best Substation Candidates:

- with load > 20MW Tx with LTC
- Potential Voltage Reduction Range is large based on load flow & accurate load model

Planning: manage unbalance and reduce voltage range
add in automatic tie-point to balance load

CVR – What does it depend on?

1. What are the loads? lighting/ air conditioner/ heater/ TV



$$\boxed{P_L = k_Z V^2 + k_I V + K_P}$$

We model loads as a ***mix*** *of constant ZIP load (static)*

**** Not possible to know exact portion of ZIP load***

2. Anything affects the load

weather

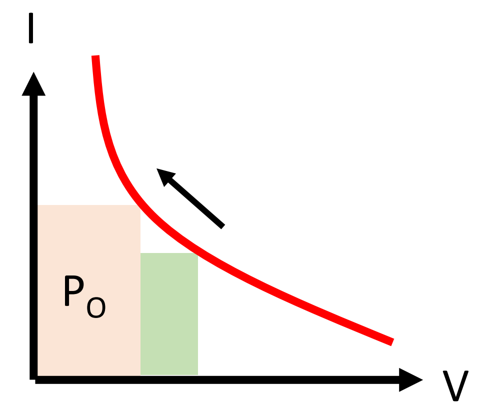
season

feeder type

3. RE Penetration

Load Mix and CVR

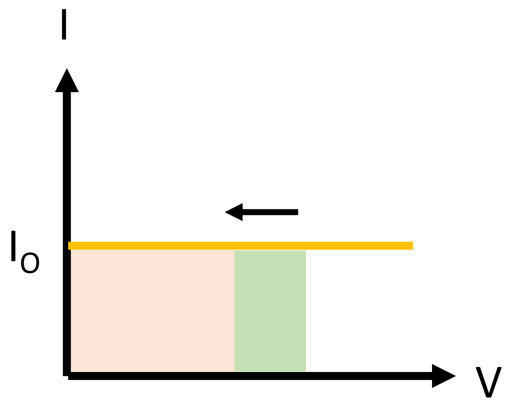
Constant power load (P-load)



Lower V, Higher I
→ Higher loss
→ Same load power

e.g. data center

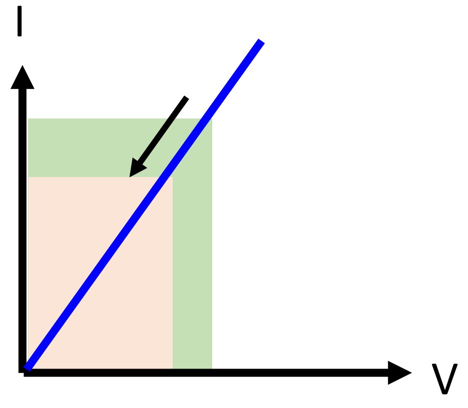
Constant current load (I-load)



Lower V, Same I
→ Same loss (I_O^2R)
→ Smaller load power

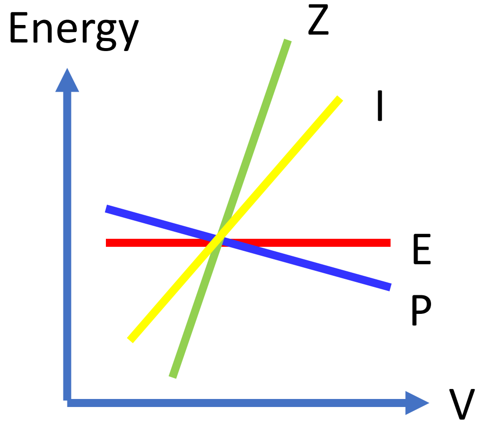
e.g. railway

Constant Impedance load (Z-load)



Lower V, Lower I
→ Smaller loss (I^2R)
→ Smaller load power

e.g. pure heater



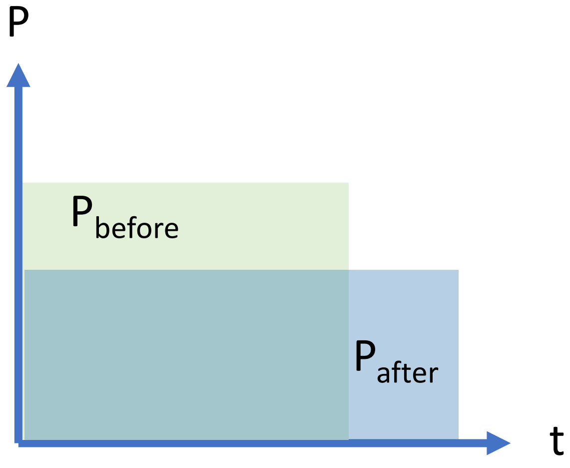
Z-load is more preferable

CVRf = 2 x %Z-load

Constant **Energy** Load describes load taking same overall energy even voltage is reduced. (e.g. heater with sensor)

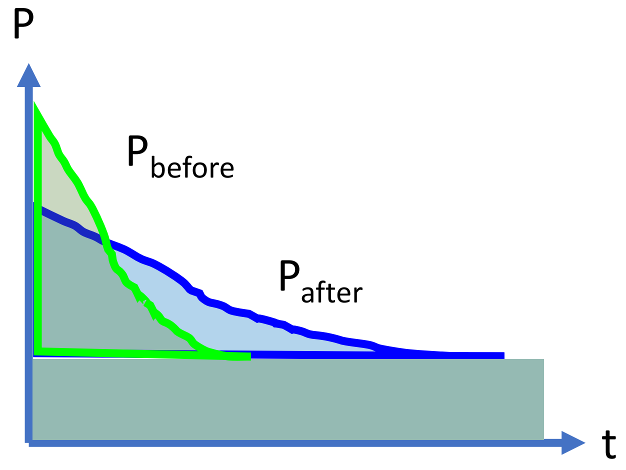
Load Mix and CVR: Constant Energy Load

1. Requires constant energy to boil an egg.



P_{before} and P_{after} should result in **same energy** to boil an egg, assuming no heat loss to the surrounding.

2. Air-con needs to remove same energy from room.



P_{before} and P_{after} should be the same as the air-con needs to remove **same energy** to cool down the room from 30^{o}C to 24.5^{o}C.

→ Same energy taken from load and same line loss (in energy), though it exhibits part of constant Z and constant P load in transient.

CVR Effects

- Seasonal Effect

CVR factor is defined as the ratio of **energy reduction** to voltage reduction for quantification.

$$CVR_{factor} = \frac{\Delta E\%}{\Delta V\%}$$

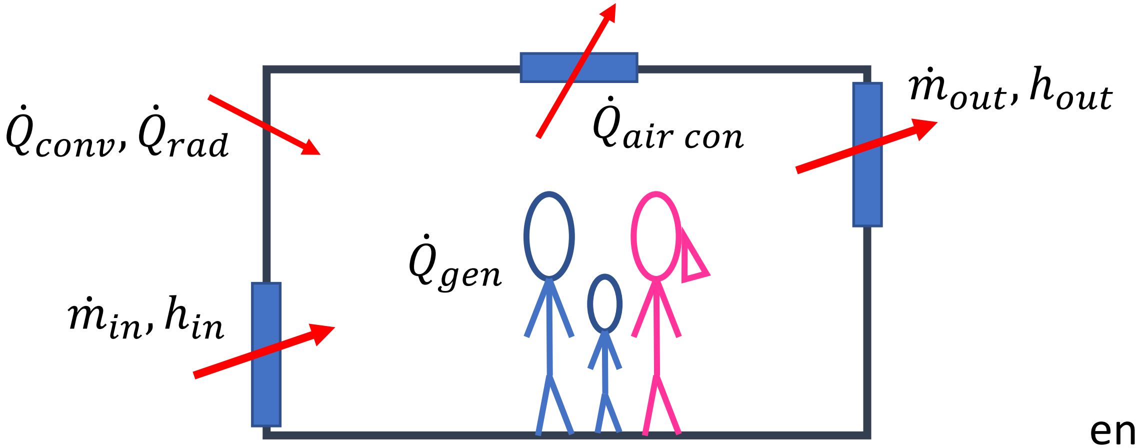
Definition of CVR factor

Utility	Winter	Spring	Summer	Fall
AEP	0.53-0.87	0.79-0.89	0.78-1.01	0.33-0.64
HQ	0.60-0.80	N/A	0.10-0.97	N/A
NEEA	0.51	0.57	0.78	0.60
BC Hydra	N/A	0.60	0.7	N/A

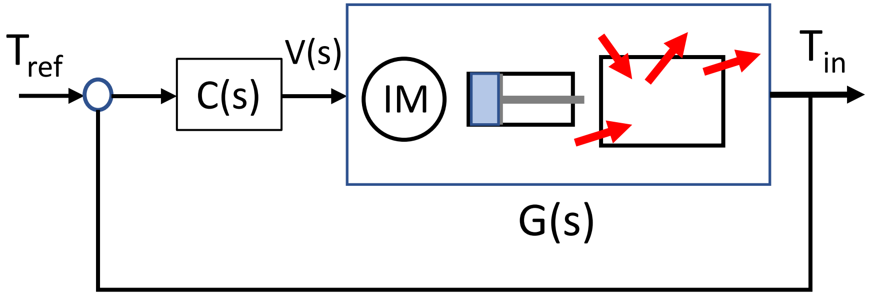
CVR factor of different seasons by utilities

In general, CVR factors in **summer are relatively higher** and those in **winter are lower**. It may be due to the large portion of **electric motor loads**, such as **air conditioners** in **summer**. **Heaters with feedback loops** come to dominate the load composition in **winter**, so CVR effects are expected to decrease. Seasonal effects of different areas are various.

Thermal Load and CVR



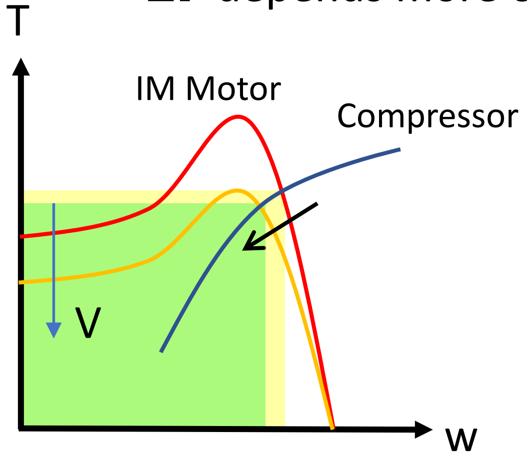
VF+ IM+ Comp +Room



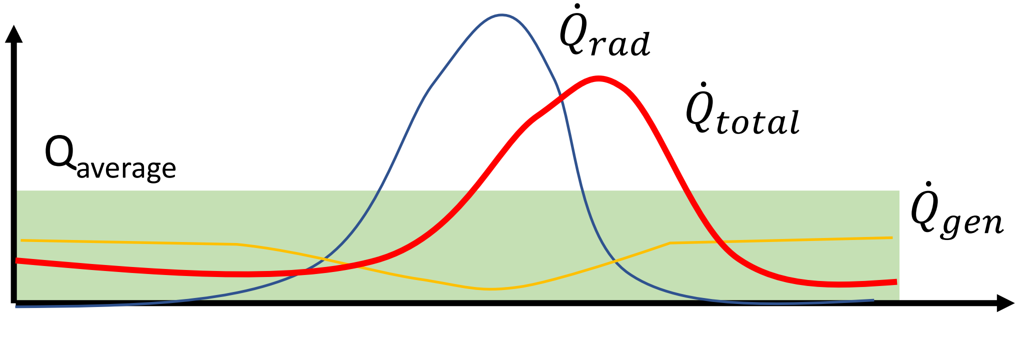
$$\underbrace{\dot{Q}_{conv}}_{\text{energy from the sun}} + \underbrace{\dot{Q}_{gen}}_{\text{energy inside the room}} + \underbrace{\dot{Q}_{mass}}_{\text{energy from mass transfer}} - \dot{Q}_{air\ con} = \cancel{\frac{dQ_{sys}}{dt}}$$

$$\dot{Q}_{air\ con} = \dot{m}_r c_p \Delta T$$

$\dot{m}_r$ depends more on w
ΔT depends more on T



Without control loop, under voltage reduction, T and w reduces, the room gets hotter, it is a Z-load. With control, VVF drives can change w to have larger $\dot{m}_r$



Radiation shows a delaying effect to energy input

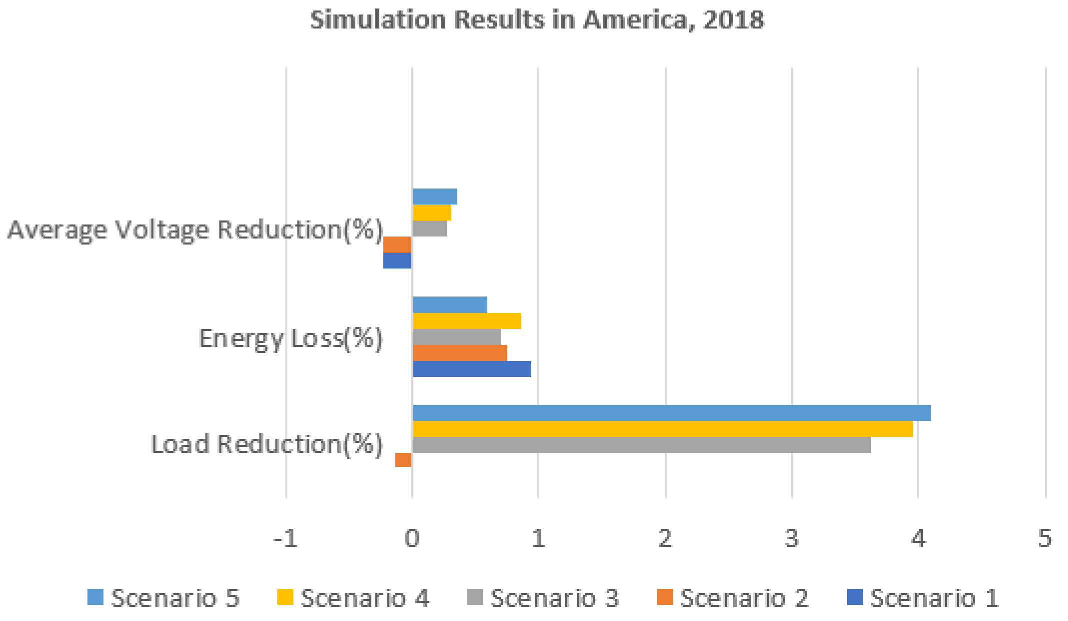
CVR Effects

- Renewable Energy Effect

(from clients) (from operators)

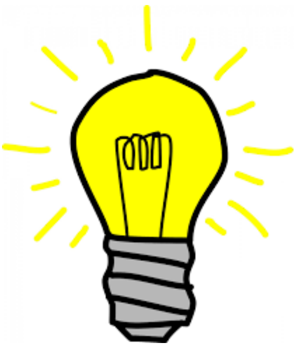
Coordinated use of **smart inverters** with legacy **voltage regulating devices** in distribution systems with high distributed PV penetration are certificated to <u>have the ability to optimize CVR performance</u>. And it is an effective way to avoid investments in voltage management equipment to tackle **voltage rise problem**.

Scenario Number	Description
Scenario 1	**No PV, No Voltage Optimization**
Scenario 2	100% PV, No Smart Inverter, No Voltage Optimization
Scenario 3	100% PV, No Smart Inverter, Legacy Voltage Control
Scenario 4	100% PV, No Smart Inverter, Legacy Voltage Control and Autonomous VVC
Scenario 5	100% PV, No Smart Inverter, Legacy Voltage Control and Aggregated **Reactive Power Control**

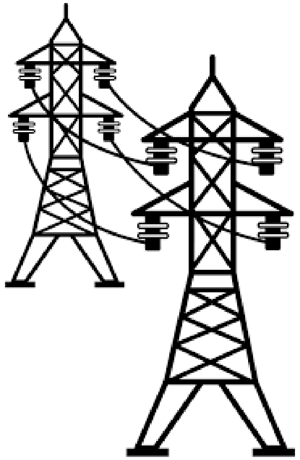


* Based on the model from IET Generation, Transmission & Distribution

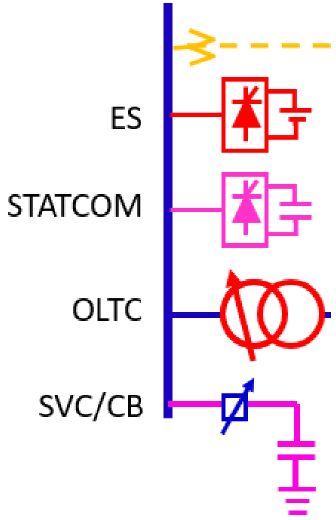
Approximated Energy/ Loss Reduction



Total Demand
= 34728GWh



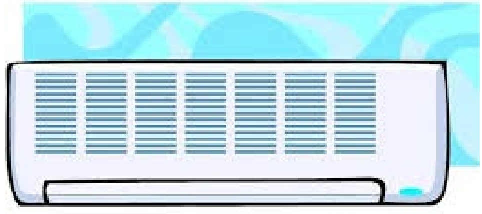
Transmission Loss
= 3.79% (1316GWh)



CVR factor = 0.55
(0.55% Power Reduction
for 1% voltage drop)

Load Reduction = 34728 x 0.55%
= 191 GWh

Loss Reduction
= $1316(1-(1-0.55\%)^2)$ = 14 GWh



Thermal load reduction
CVR factor = 0.275

Load Reduction = 34728 x 0.275%
= 99.5 GWh

Loss Reduction
= $1316\ (1-(1-0.275\%)^2)$ = 7 GWh

A Short Summary

CVR Effects

- **Load reduction and energy reduction**: up to 4%. **Loss reduction** is a side-effect
- Vary with **seasons**, normally more effective in summer than winter
- Behave differently with **load types**, normally more effective on “Z” load and “I” load than “P” load
- Available in distribution system of **high RE penetration**

CVR Benefits

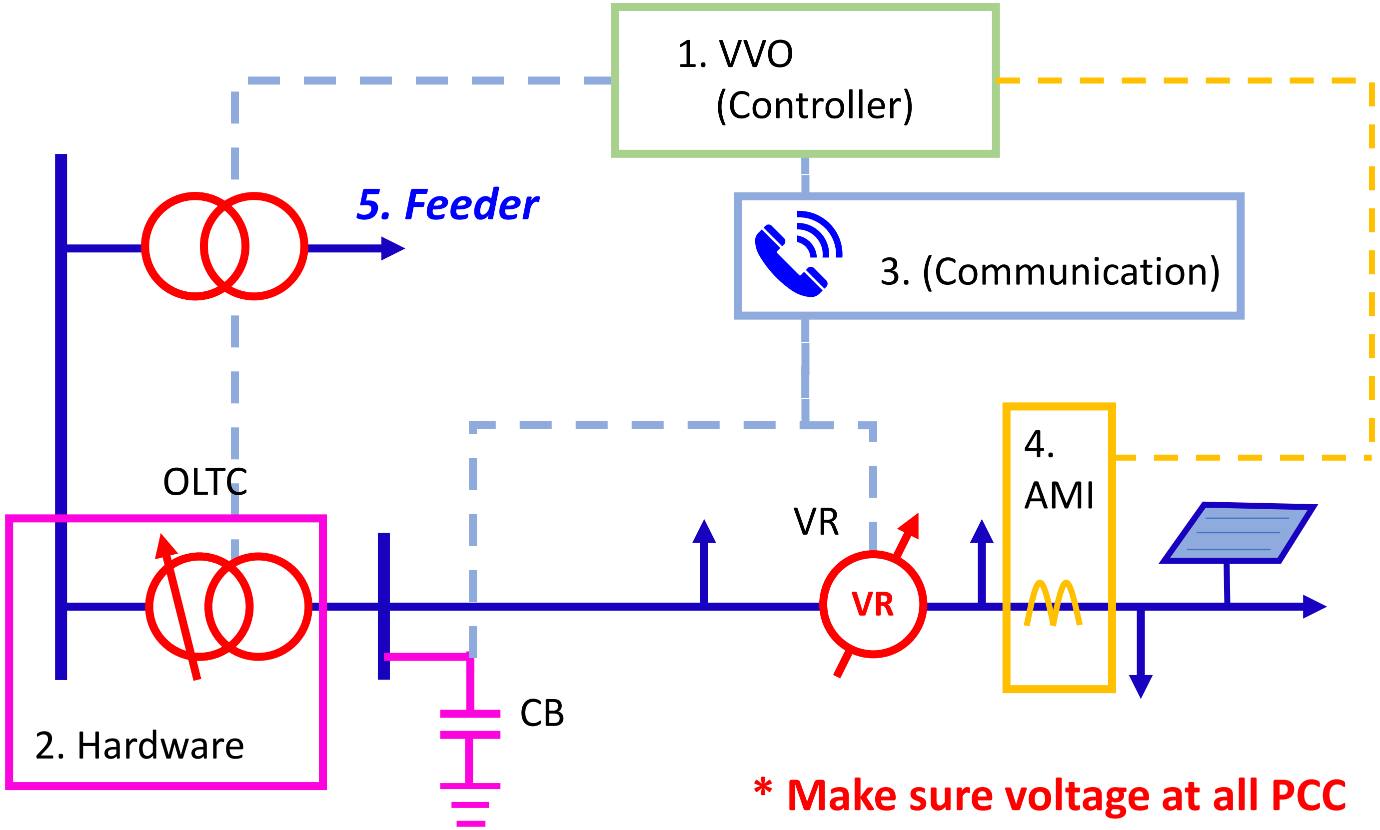
essential to study the **potentials** for CVR applications.

- A high-efficient technology **applied worldwide by other utilities** and studied widely in research
- Promote **energy efficiency** and embrace **energy saving** → lower carbon emissions, less fuel consumption
- Useful to tackle **renewable voltage rise issues (voltage control)** and higher demand in future **extreme weathers (peak load reduction)**
- Normally no revenue loss: **lower energy sales** are normally far **outweighed** by the **demand reduction savings**

Scope of Studies and Requirement

- Find out the effectiveness of conservative voltage reduction (i.e. CVRf) under different conditions (load mix, weather & season, penetration of RE) & the actual line loss reduction & energy reduction.

- Required Components:
  - feeders
  - volt-var control components (OLTC)
  - metering devices (CT, VT)
    * at feeder end & all PCC
  - communication & control devices (SCADA)



*** Make sure voltage at all PCC lives within boundary**

Highlights

(5)

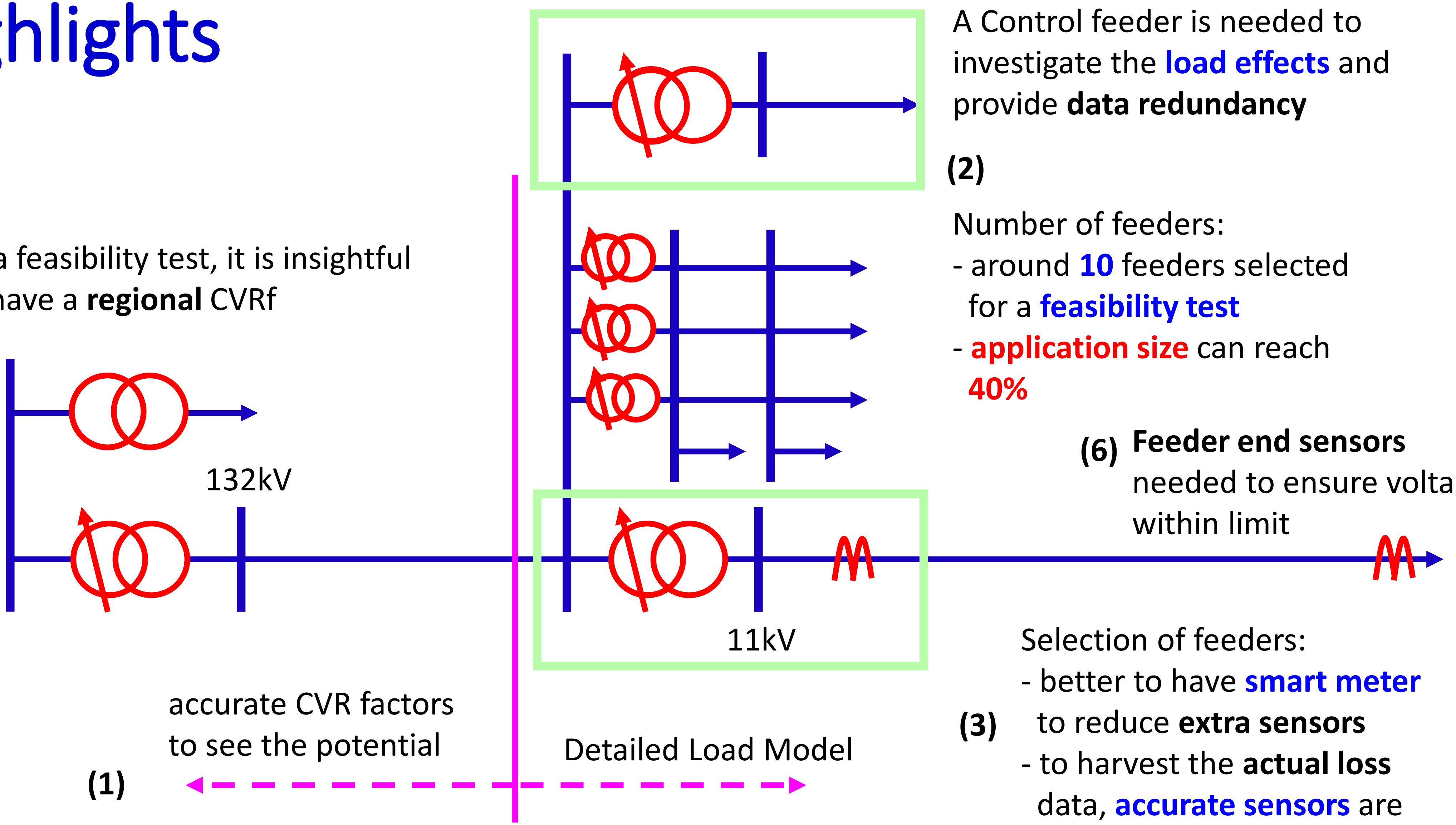
A Control feeder is needed to investigate the **load effects** and provide **data redundancy**

(2)

Number of feeders:
- around **10** feeders selected for a **feasibility test**
- **application size** can reach **40%**

(4)

As a feasibility test, it is insightful to have a **regional** CVRf



(6) **Feeder end sensors** needed to ensure voltage within limit

(3)

Selection of feeders:
- better to have **smart meter** to reduce **extra sensors**
- to harvest the **actual loss** data, **accurate sensors** are needed.

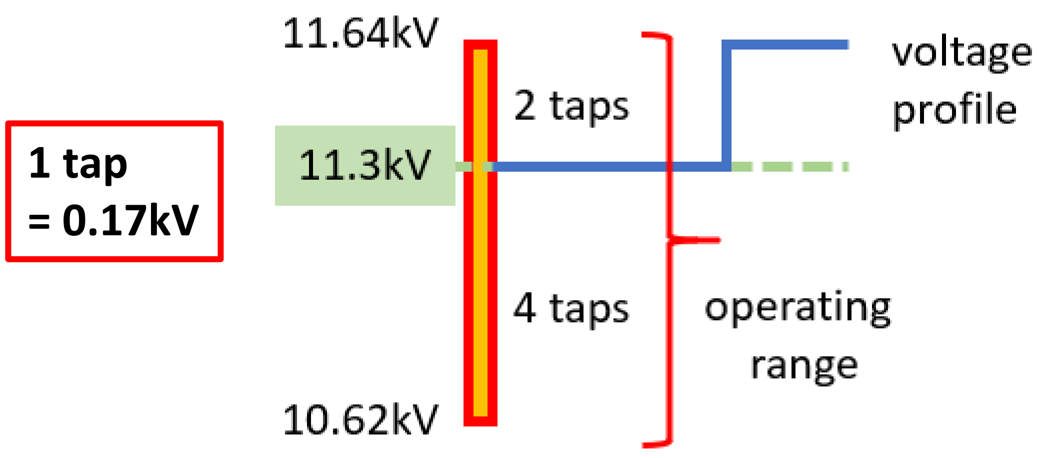
(1)

accurate CVR factors to see the potential

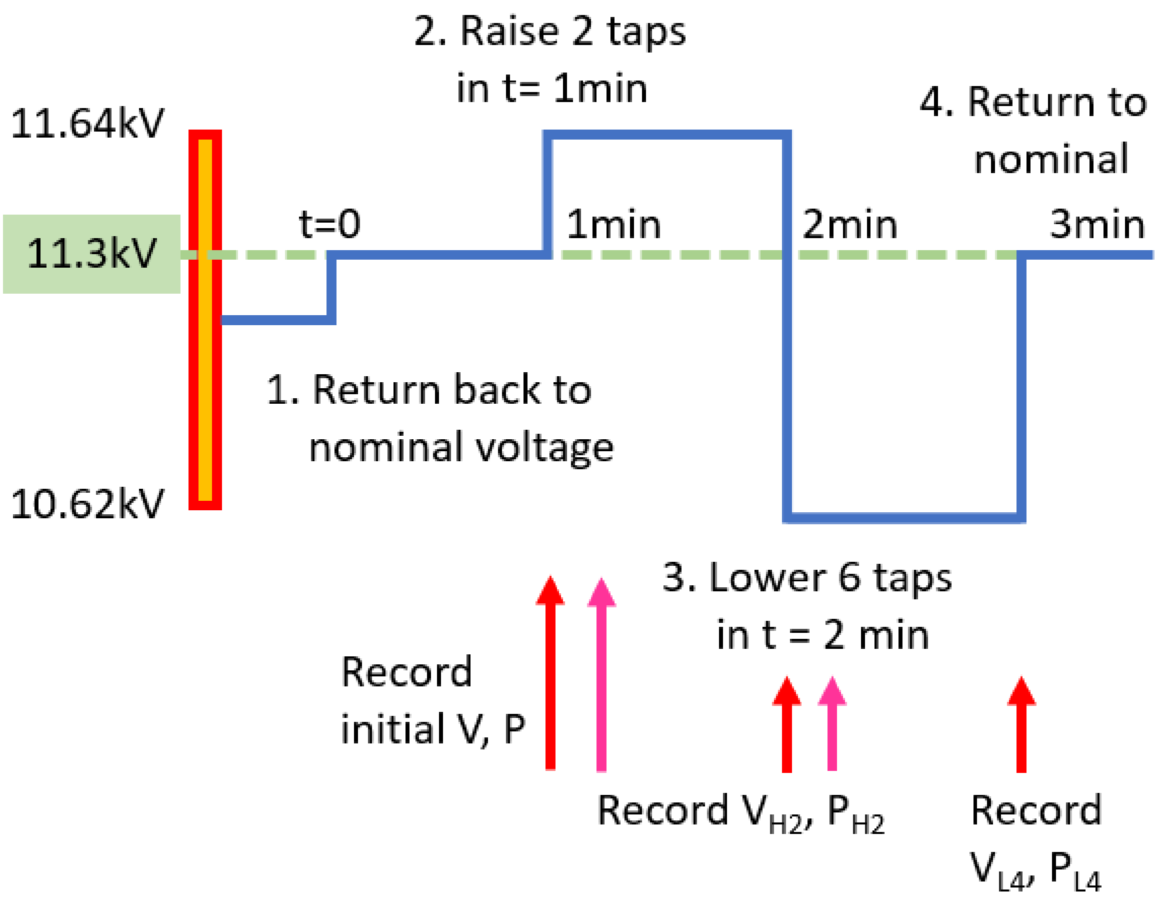
Detailed Load Model

Testing Procedures I

Testing Range



Testing Procedures



* P, Q should be clearly differentiated (*power angle*)
* Record the voltage and current at **5s, 1min, 5min, 30 min** if needed (avoid transient effect)
* The dP/dV value will be found by *simple averaging*. (can be discussed in next stage)

Testing Procedures II

To make the test more accurate, **more feeders** can be selected and the test can be reiterated for **more times** to take more data.

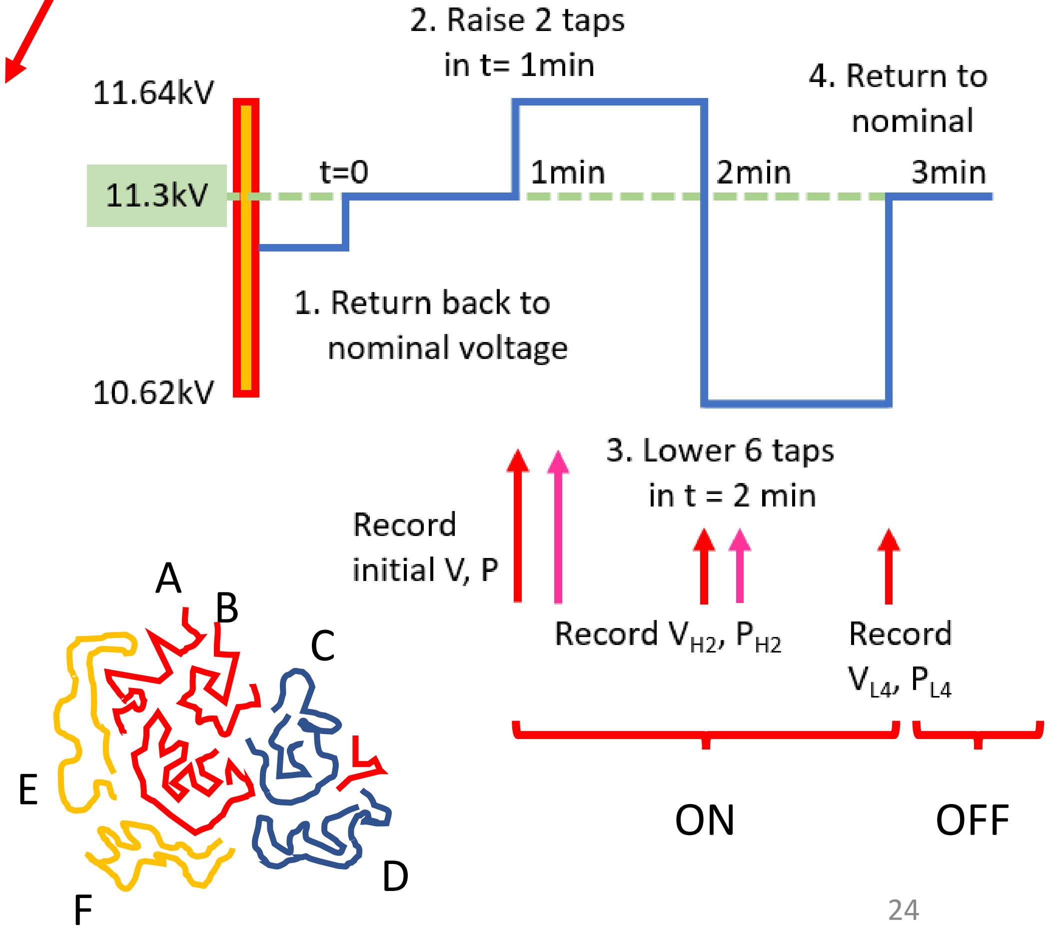
	Industrial	Residential	Commercial
Control	Feeder A	Feeder C	Feeder E
Test	Feeder B	Feeder D	Feeder F
	…	…	…

<ins>Test 1: Feeder Type (time)</ins>

Select feeders with similar loading (P, Q)

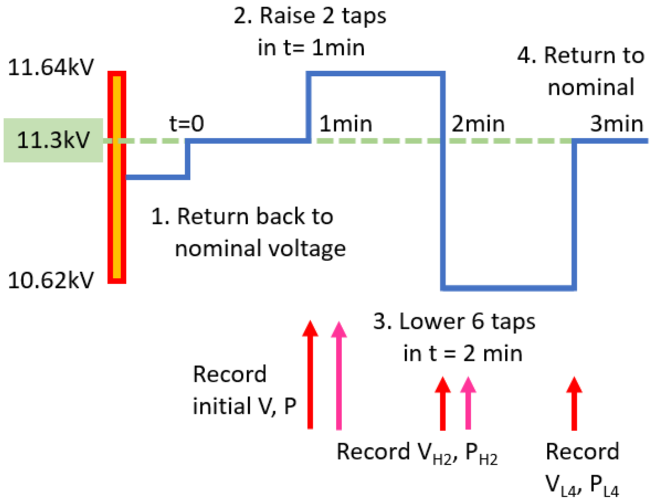
	Initial V	Initial P	Initial Line Loss	V_{H2} at 5s	P_{H2} at 5s	dP/dV (5s)	V_{H2} at 1min	P_{H2} at 1min	dP/dV (1min)
Feeder A									
Feeder B									
Feeder C									
Feeder D									
Feeder E									
Feeder F									
	Line Loss at H2		Line Loss at L4	V_{L4} at 5s	P_{L4} at 5s	dP/dV (5s)	V_{L4} at 1min	P_{L4} at 1min	dP/dV (1min)
Feeder A									
Feeder B									
Feeder C									
Feeder D									
Feeder E									
Feeder F									

Apply Voltage Profile to all feeders.



Testing Procedures III

Possible to have transient effect/ load changing



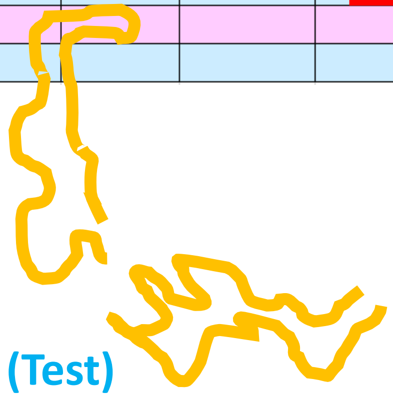
Longer time
= Clearer effect

Test 2: Feeder Type with/without CVR (Space)

	Initial V	Initial P	Initial Ploss	V at 5s	P at 5s	dP/dV (5s)	V at 1min	P at 1min	dP/dV (1min)
Feeder A									
Feeder B									
Feeder C									
Feeder D									
Feeder E									
Feeder F									

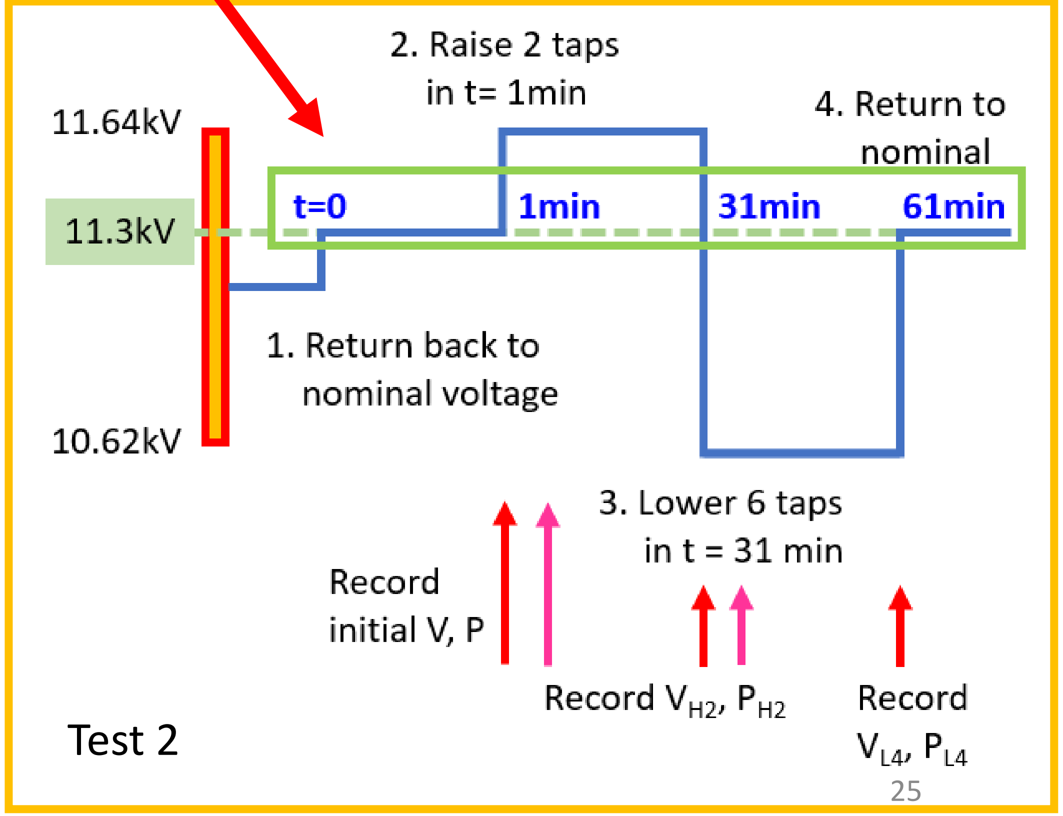
	Line Loss H2		Line Loss H4	V at 5s	P at 5s	dP/dV (5s)	V at 1min	P at 1min	dP/dV (1min)
Feeder A									
Feeder B									
Feeder C									
Feeder D									
Feeder E									
Feeder F									

compare at
the same time



E (Control)

F (Test)



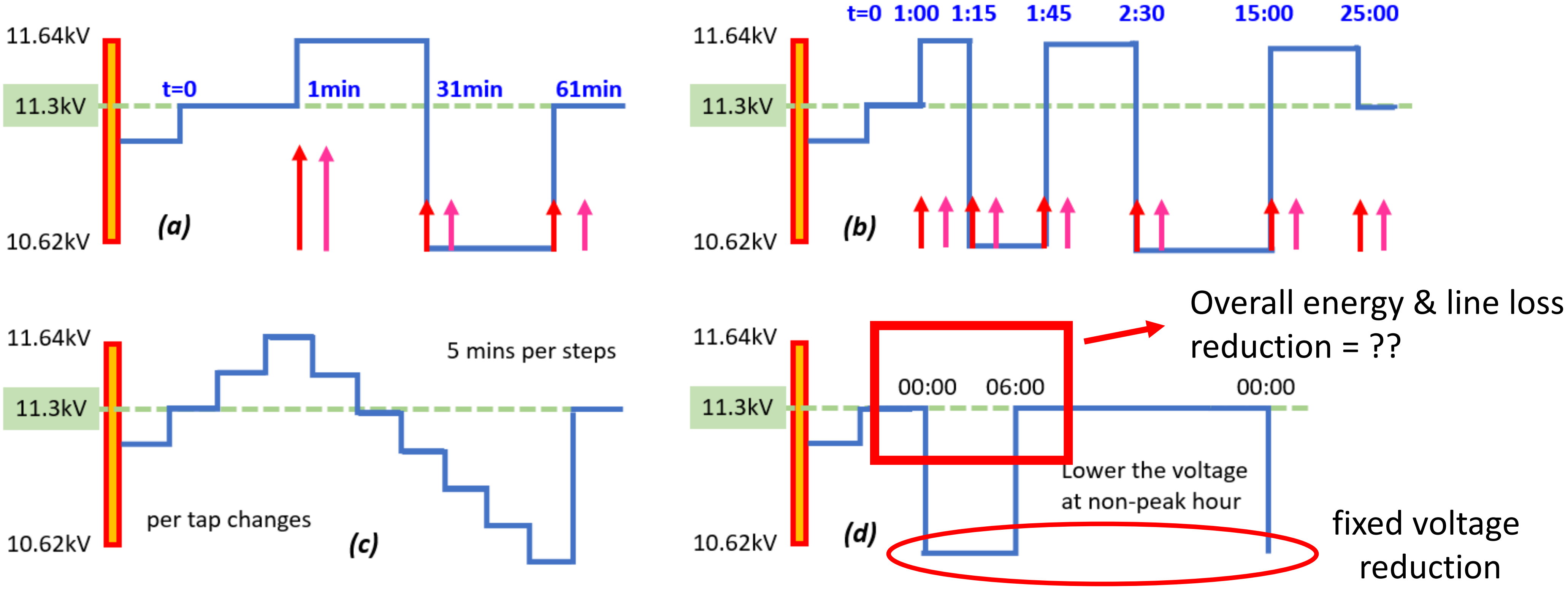
* In this test, A, C, E are reference and B, D, F are tested sample.

Testing Procedures IV

Smaller time step better than larger time step?
Variable time step better than fixed time step?

Does time step affect CVRf?

Test 3: Different Voltage Profiles



Does initial voltage affect CVRf?

Perturb & Observe better than sudden change?

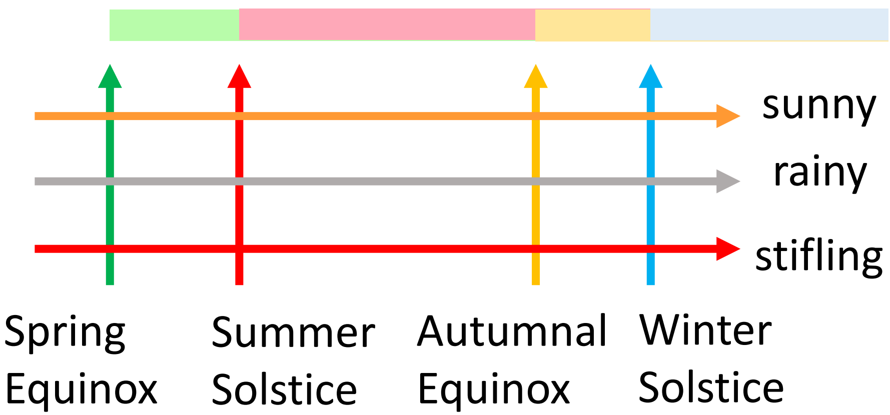
Does time to apply affect CVRf?

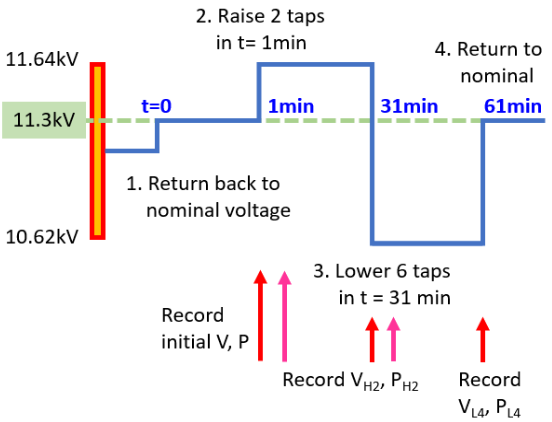
Fixed Voltage Step more approachable than Variable?

Testing Procedures V

<u>Test 4: Seasonal Effect / Weather Effect</u>

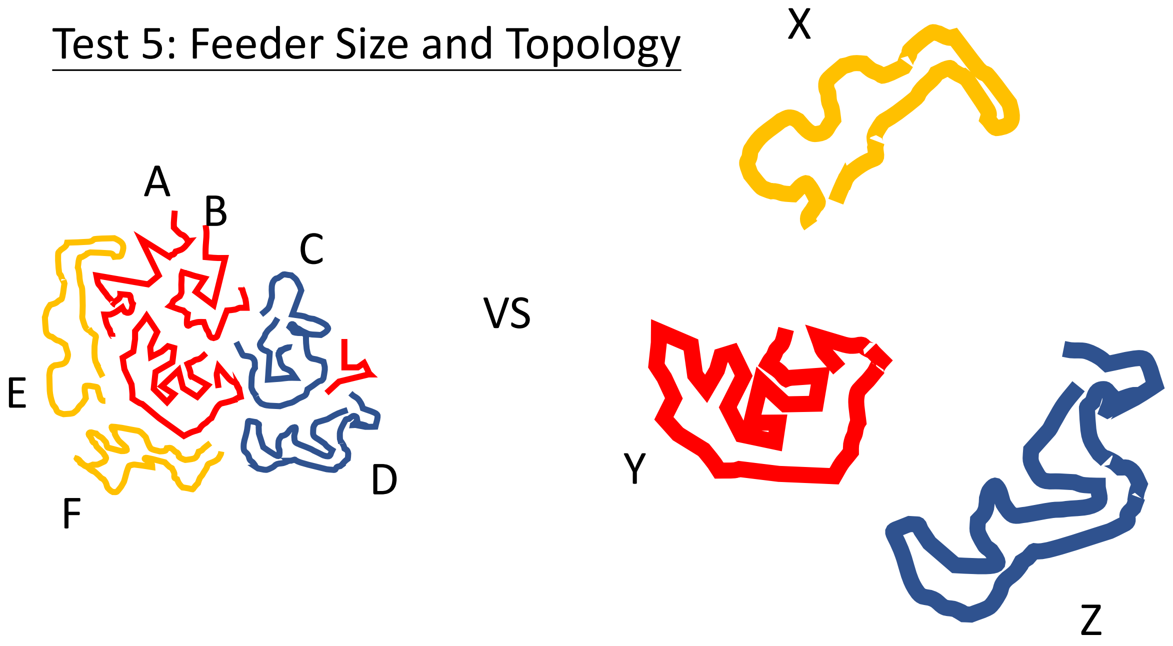
12 sample days





Standard ***Long Time Testing*** with ***A, C, E as reference***.

<u>Test 5: Feeder Size and Topology</u>



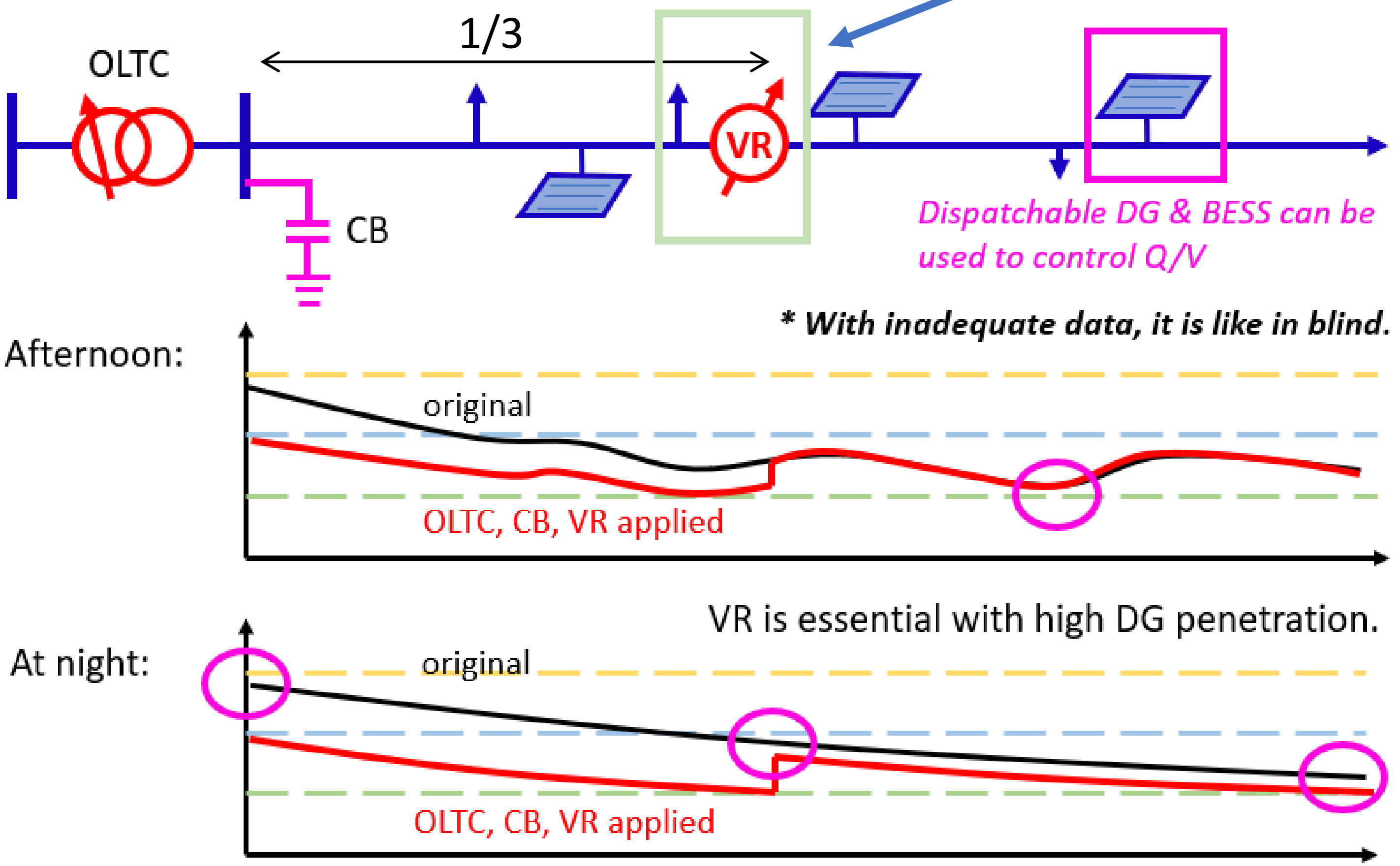
Select 3 feeders with 10x power flow as compared to the base

Reported case:
1. For ring/ grid, lowest voltage point is near the center.
2. Larger systems has significant effect on loss reduction.

Testing Procedures VI

Test 6: (Optional) Penetration of Renewable Energy

A VR is installed.



* Higher penetration
  = higher **voltage rise** issue

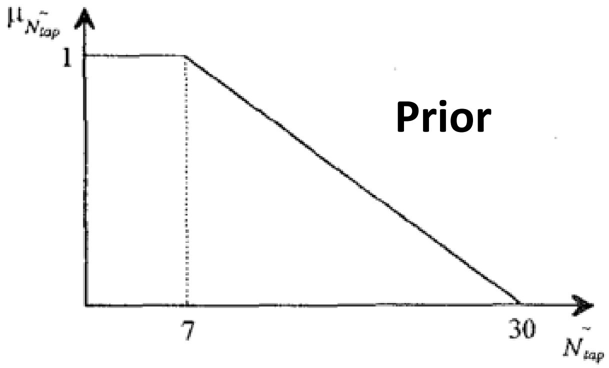
* At client side, the inverter should be able to control the voltage.
* At operator side, volt-var components should be there to ensure voltage lying within limit.

* With Voltage rise issue, all PCC voltage is possible go over the boundary → voltage sensors are needed as well.

* Questions on **number of steps** needed in a day.

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

Testing Procedure VII



Test 7: (Optional, Final Goals) Perform **Optimization** to obtain **CVR Schedule**

The operation of LTC and CB in I = 1-24 hours can be represented with the following objective function.

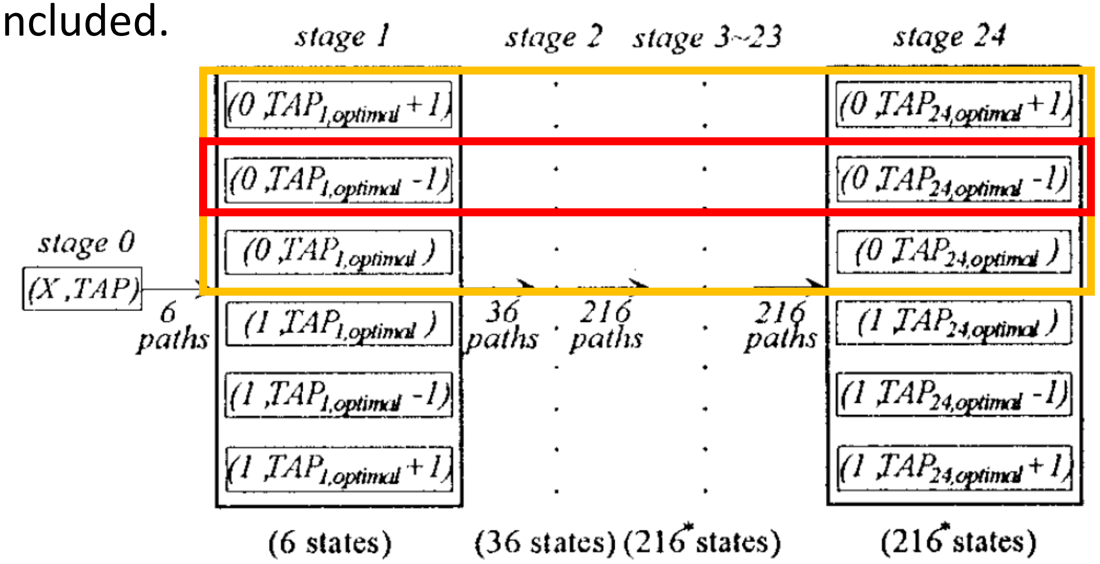
$$J = \sum_{i=1}^{24} \mu_{\Delta V_{2_i}} + \sum_{i=1}^{24} \mu_{pf_i} + \mu_{N_{tap}} + \mu_{N_C} \qquad \text{subject to} \qquad \begin{array}{c} N_{tap} = \Sigma\,(TAP_i - TAP_{i-1}) \le 30, N_C \le 6, \\ V_{min} \le V \le V_{max}, pf_{min} < pf \end{array}$$

where $\mu_{\Delta V_{2_i}}, \mu_{pf_i}, \mu_{N_{tap}}, \mu_{N_C}$ are the membership function of the requirements, and TAP_i is the tap position at hour i.

Prior can be included.

Load Forecasting

Simulation & Optimization



Way Forward

Conservative Voltage Reduction (CVR):
Improve energy efficiency & Promote energy saving

Volt-Var Optimization (VVO):
Improve distribution grid operation efficiency under penetration of RE

Advanced DMS
Automate and Optimize the systems with accurate modelling and advanced sensing

	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

Conclusion

- CVR trials is a must DO trial to:
  1) get familiar with our load types,
  2) get ready for extreme weather with increasing demand,
  3) take care of increasing RE penetration.
- Although CVR mainly aims for **energy and peak reduction**, it may not necessarily reduce utility revenue with constant energy load (such as air con) consuming fixed amount of energy over time period. As such, it will not significantly reduce energy while **line loss** could be reduced.
- CVR trials can deduce **CVR factors** but not the *detailed load model*.
- CVR were performed in utilities worldwide and **feasibility test** were done. It is to investigate the **potential** of CVR implementation. Overall, CVR is a promising technique to promote energy saving and improve energy efficiency.
- The detailed testing procedures and considering factors are proposed.
- **VVO and ADMS** are possible for future implementation to improve operational efficiency in distribution network.