# SMART GRID Technologies

PE/PE/HT/324C

Professional Elective Course

# Smart Grid Technologies

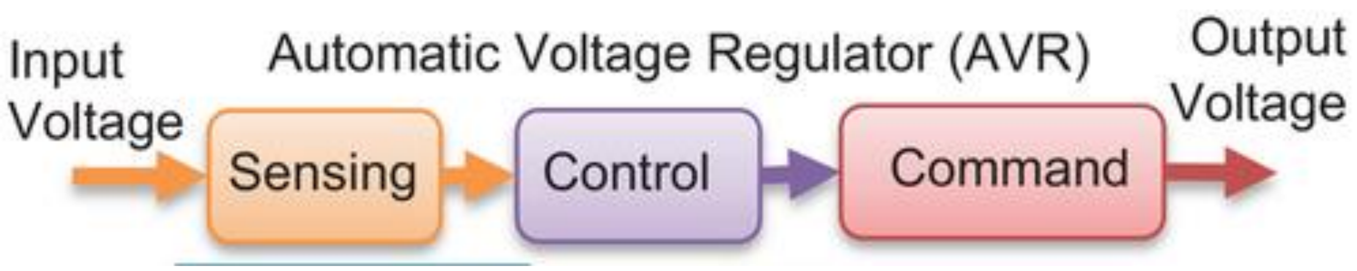
- Automatic Generation Control (AGC)
- **Automatic Voltage Regulation (AVR)**
- Energy Management System (EMS)
- Distribution Management System (DMS)
- Demand Side Management (DSM)
- Outage Management System (OMS)
- Wide Area Management System (WAMS)
- Advanced Metering Infrastructure (AMI)
- Meter Data Management (MDM)
- Geographical Information System (GIS)

# Automatic Voltage Regulation (AVR)

One of the main objectives of electric utilities is to maintain the grid voltage within standard levels to guarantee customers' satisfaction

Automatic voltage regulators (AVRs) are employed to stabilize the terminal voltages of medium, high, or extra high voltage power grids

AVR helps to keep the voltage profiles within the allowable limit



# Automatic Voltage Regulation (AVR)

Many AVR equipment are deployed in the grid

- Generator excitation controller
- On Load Tap Changers (OLTCs) for transformers
- Capacitor banks
- FACTS devices, etc.

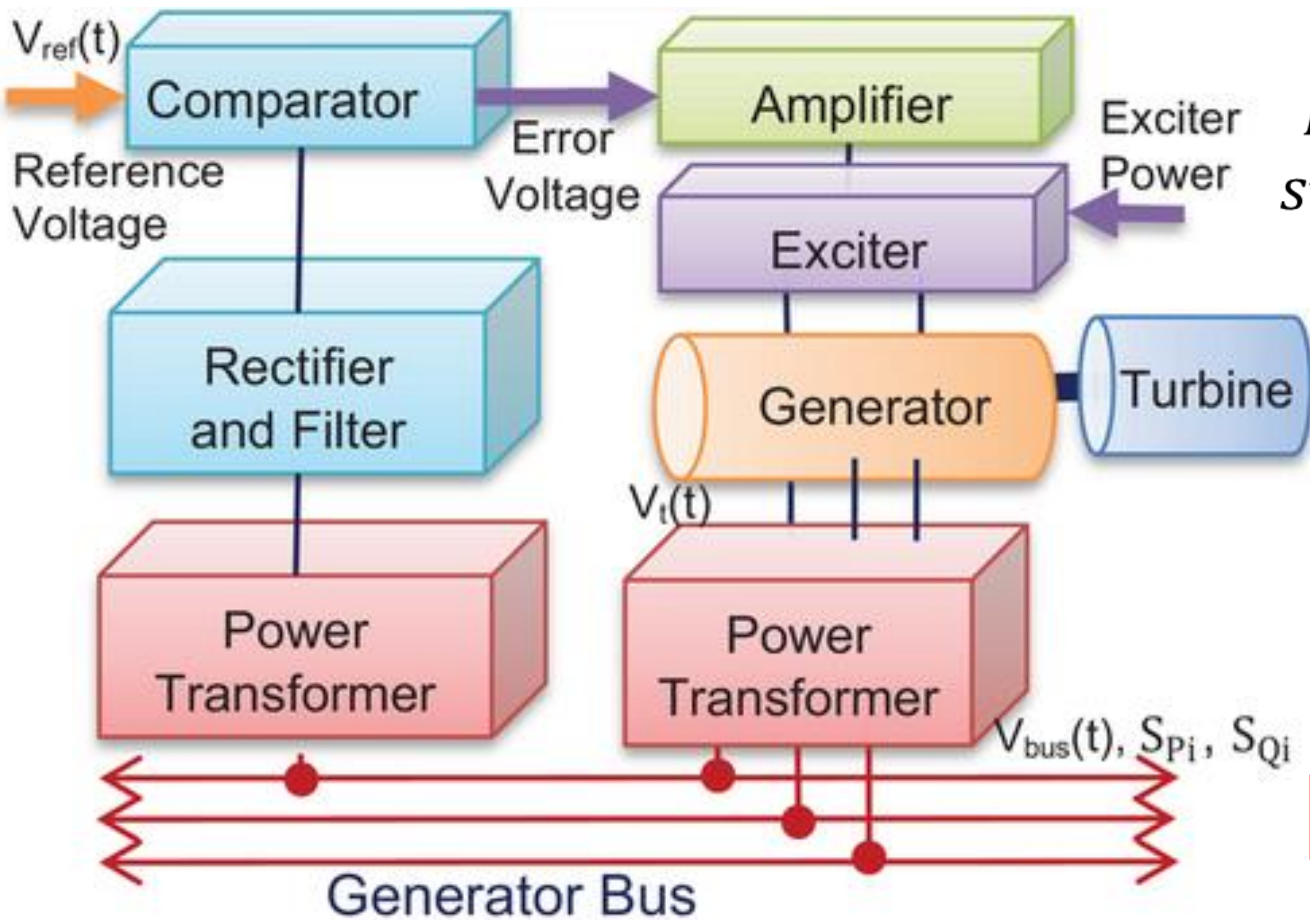
# Automatic Voltage Regulation (AVR)

Voltage regulation is considered one of the main operational challenges that accompany high penetration levels of renewable-based DGs

RES, such as wind and solar energy, can significantly change the voltage profile of smart grids and interact negatively with conventional schemes of controlling onload tap changers (OLTCs)

# Generator AVR System

Generator AVR systems constitute an exciter, an amplifier, and a sensor-based feedback system.

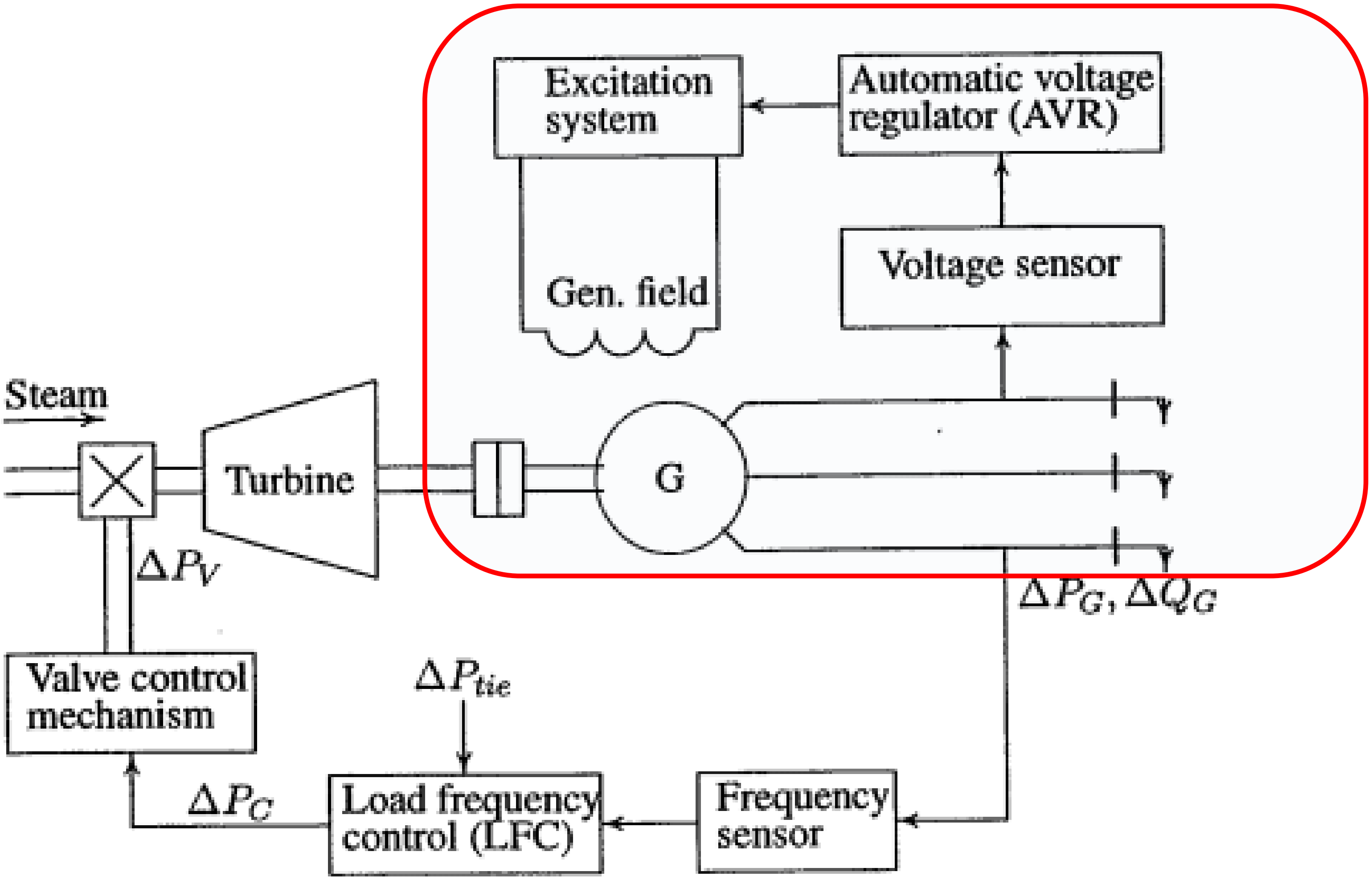



*DC voltage for supplying field p*

$$E_f = 4.44 f \emptyset_m T K_w$$

# Generator AVR System

Generator AVR systems constitute an exciter, an amplifier, and a sensor-based feedback system.

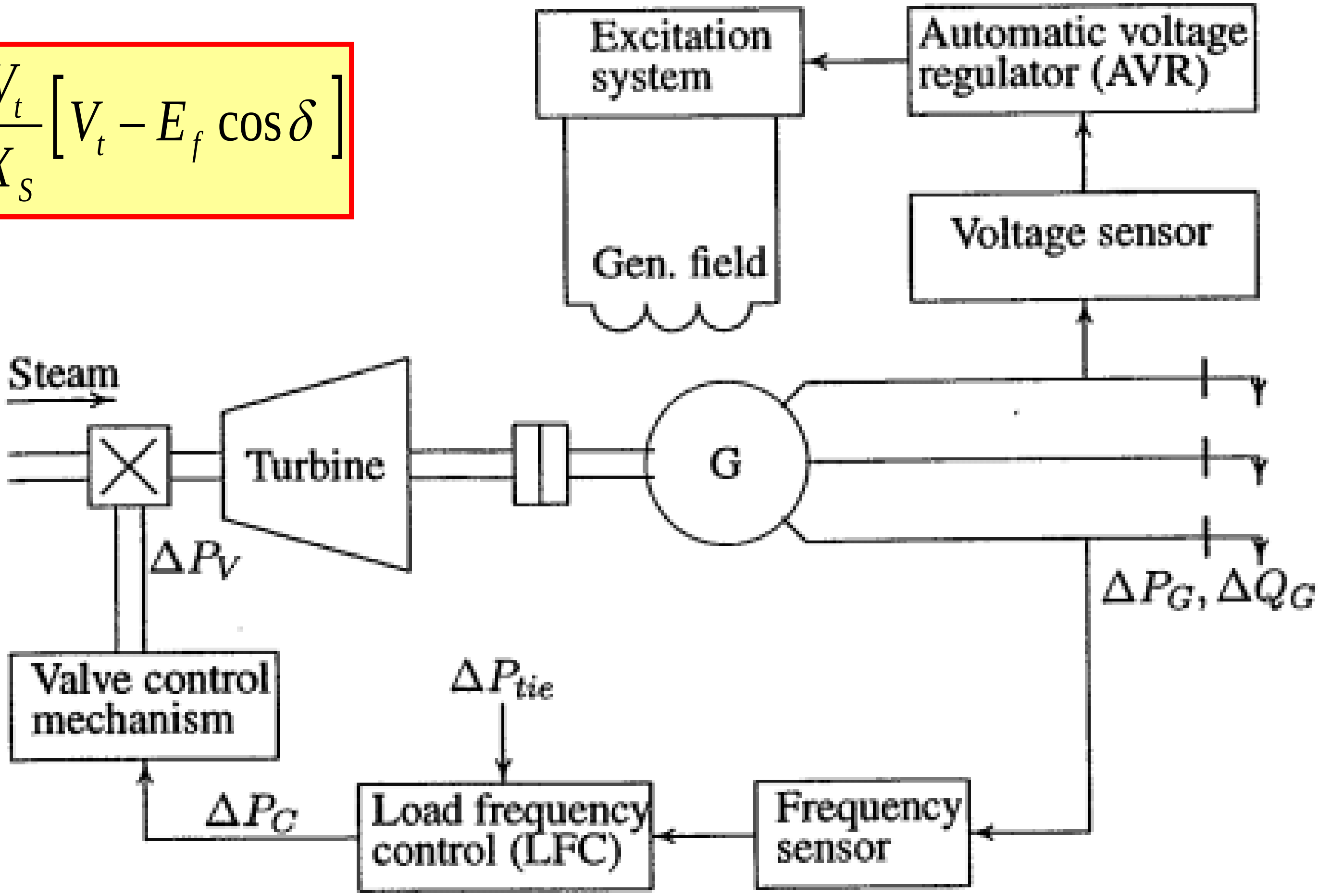


# Generator AVR System

The reactive power and the magnitude of voltage are controlled by the Automatic Voltage Regulator (AVR) loop.

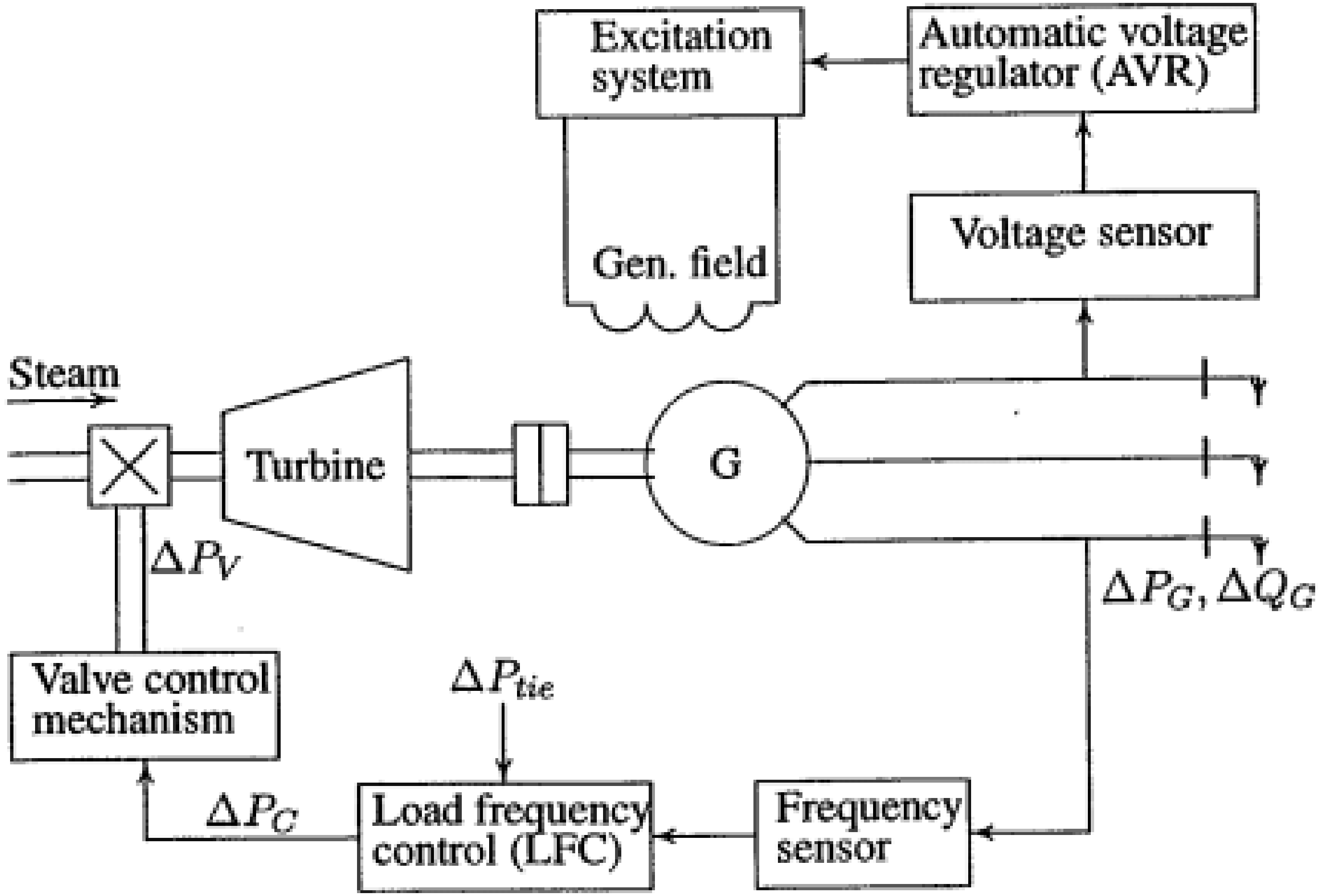
$$E_f = 4.44 f \emptyset_m T K_w$$

$$Q_{im} = \frac{V_t}{X_S}\left[V_t - E_f \cos\delta\right]$$



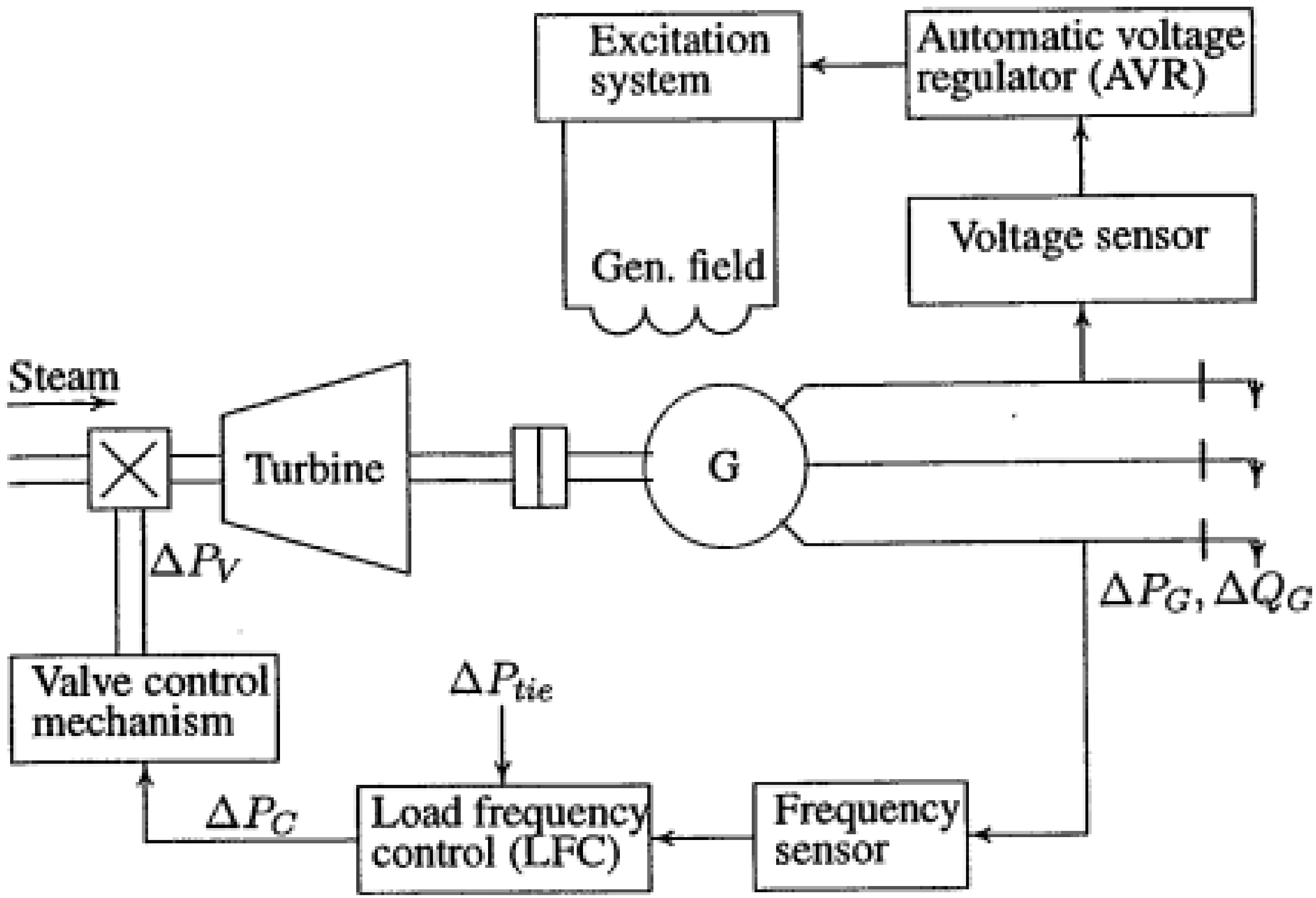
# Generator AVR System

The objective of AVR is to maintain the terminal voltage of the generator constant at nominal value during normal operating conditions at different load levels



# Generator AVR System

The excitation system of AVR control loop employs terminal voltage error to change the field voltage to control the generator terminal voltage.

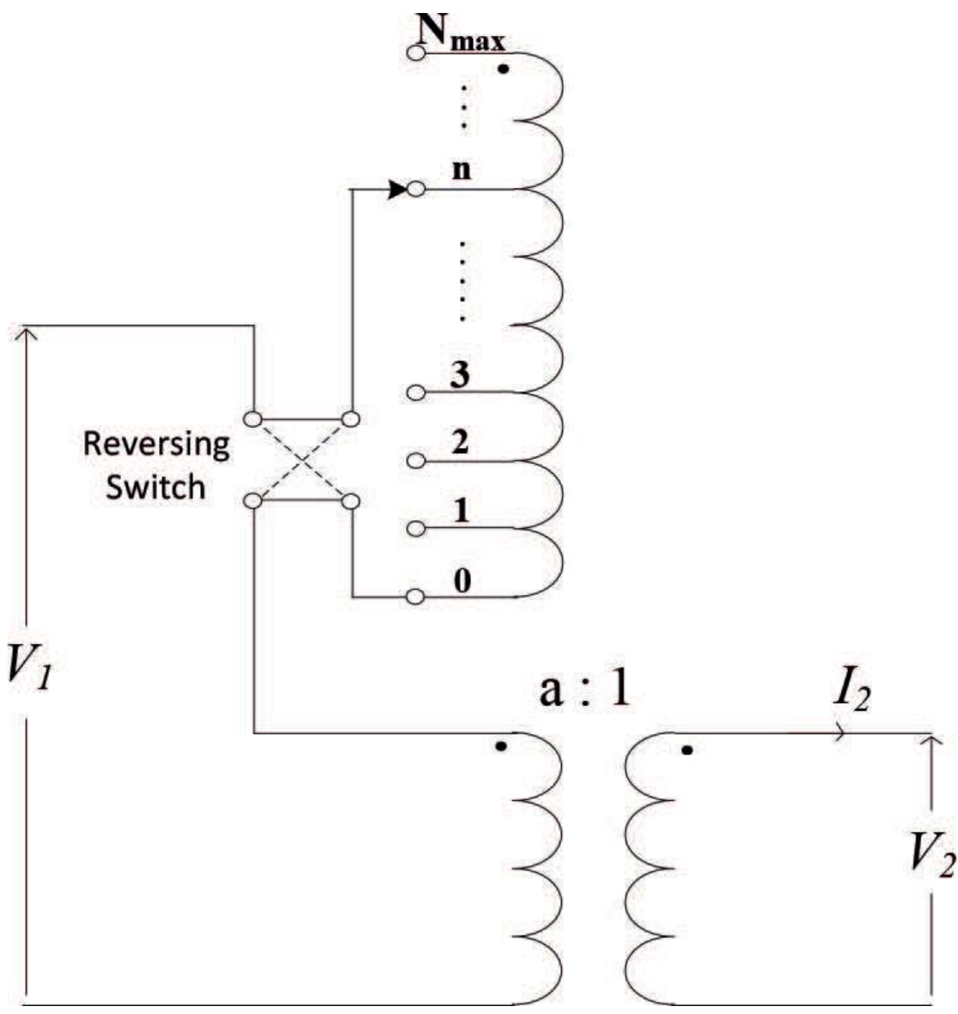


# AVR for Transformer Tap Changing

**On Load Tap Changer (OLTC) conventional controller:**

OLTCs are one of the main voltage regulators in distribution systems

A tap changer equipped with an automatic control system usually regulates the transformer's secondary voltage to maintain an acceptable voltage near the load center



# AVR for Transformer Tap Changing

However, traditional mechanical OLTC has some disadvantages:

- big volume
- complicated structure
- slower action speed
- arc caused by switching operation
- disability to control accurately

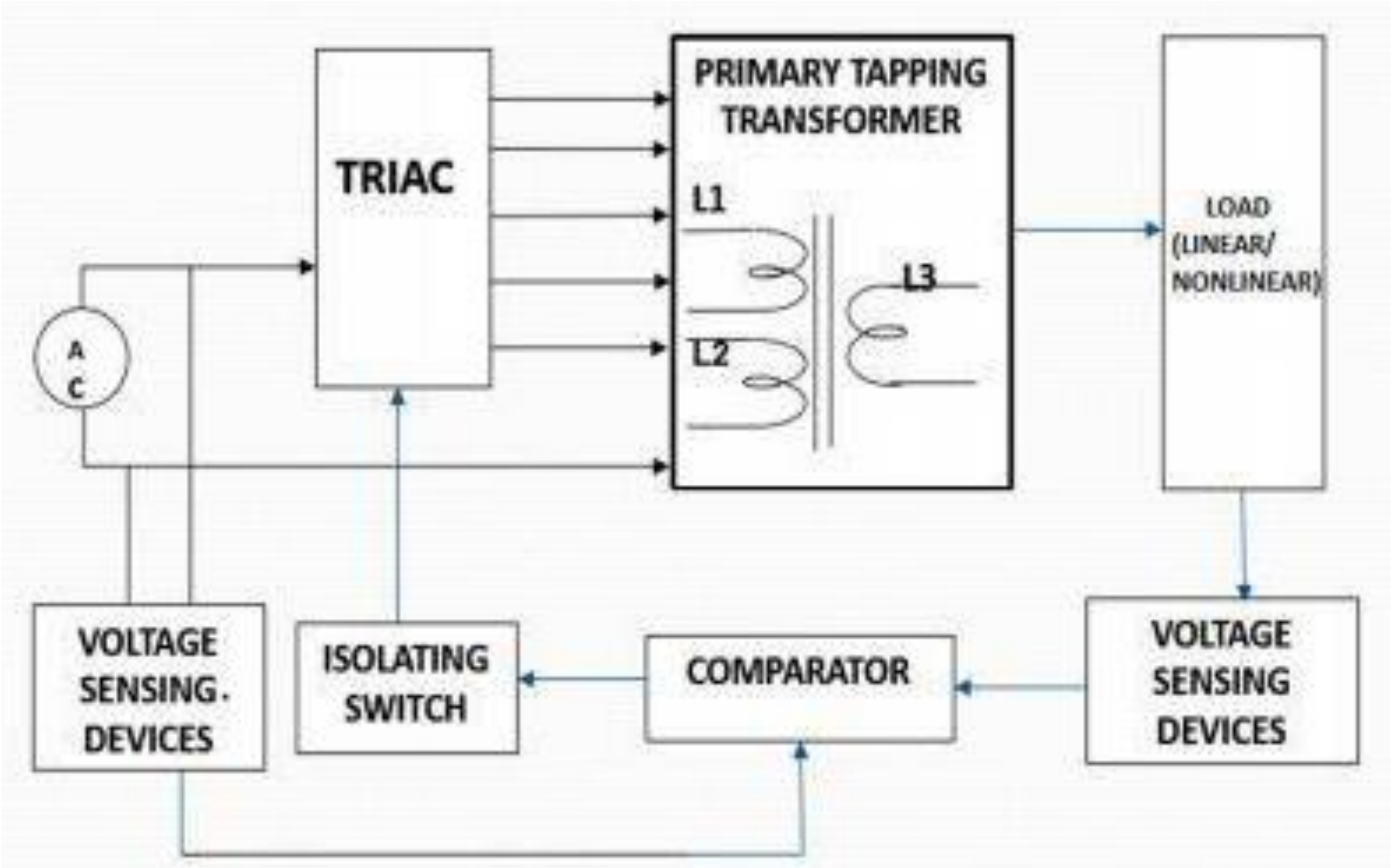
In recent years, the electronic OLTC and the hybrid OLTC, which switch the current lines with the assistances of power electronic devices, have been used

In addition, the software and hardware based on digital signal processer (DSP), AD sampling circuit, signal conditioning circuit, MOSFET driving circuit, over-voltage absorption circuit, and so on, have been developed

# AVR for Transformer Tap Changing

## OLTC conventional controller:

- The tap changer physically varies the tap position from zero (no voltage compensation) to $N_{max}$ (maximum voltage compensation)



# AVR using Static Compensators (STATCOM)

Transmission line parameters such as

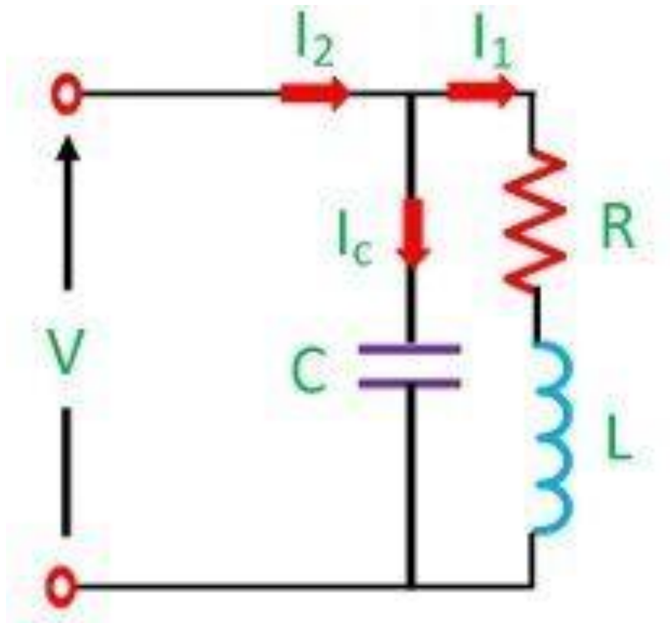
- Impedance
- terminal voltage
- voltage angle

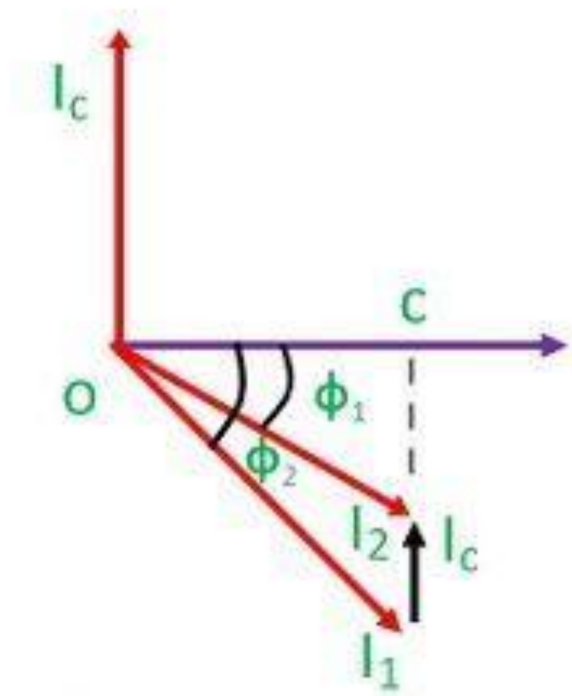
Can be controlled quickly and effectively using bank capacitors and Flexible AC Transmission System (FACTS) devices to improve the voltage profile

# AVR using STATCOM

Bank capacitors usually used to provide:

- reactive power compensation
- power, and voltage loss compensation
- voltage stability on buses
- improve system security

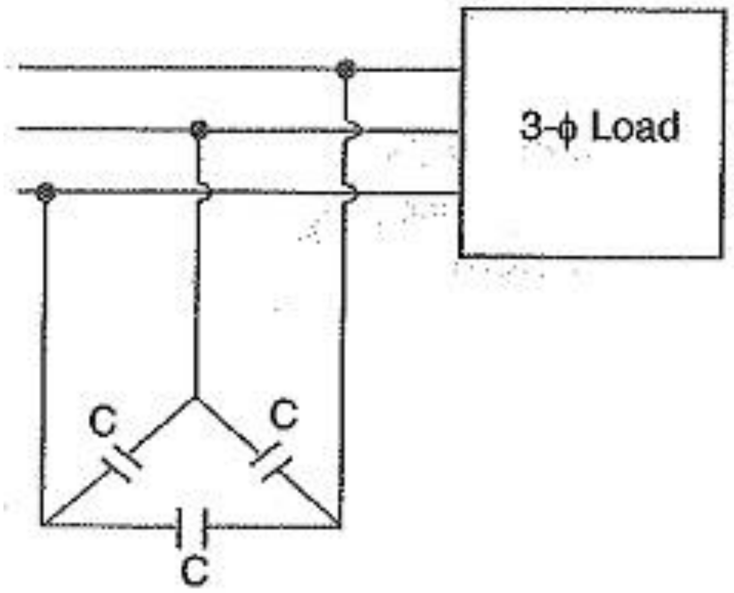


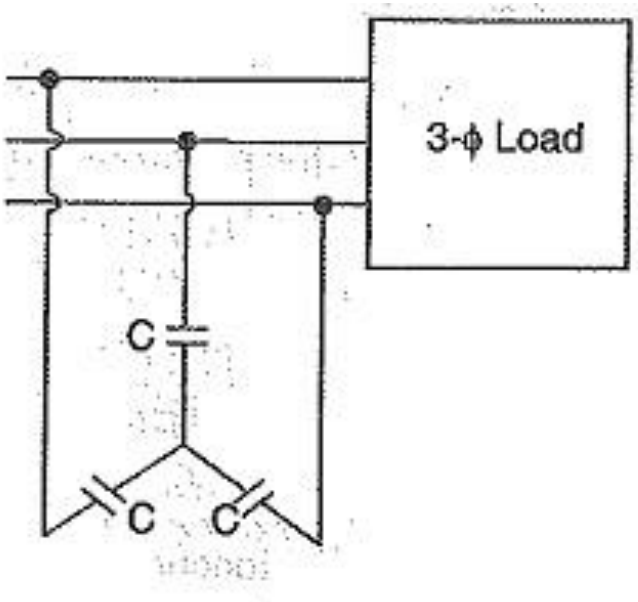



# AVR using STATCOM

The capacitor unit is parallelly connected to meet the needs of:

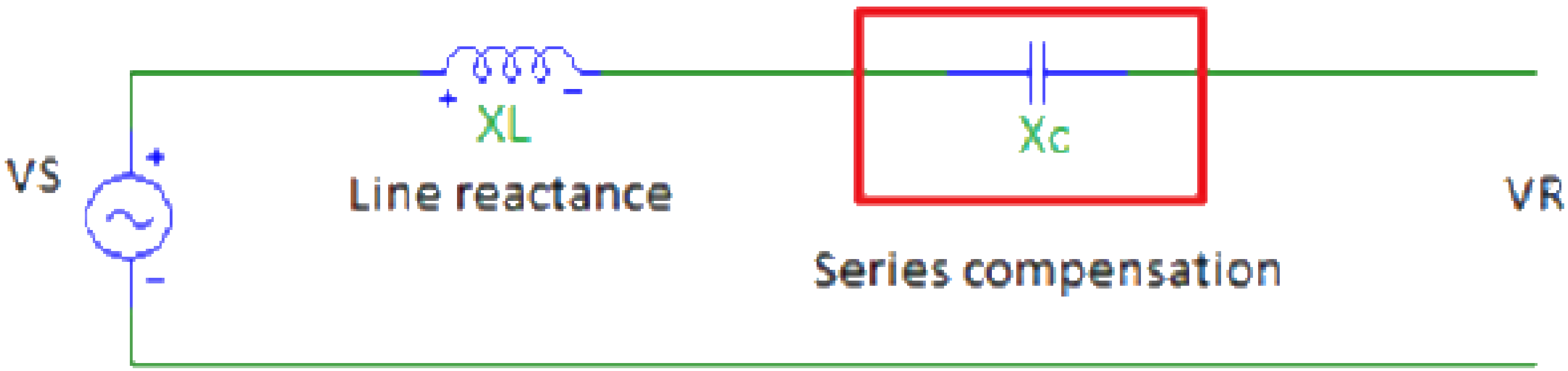
- reactive power (MVAR)
- stabilizing the voltage



# AVR using STATCOM

Capacitor units are connected in series only to meet voltage improvements by compensating the inductive loading of the circuit

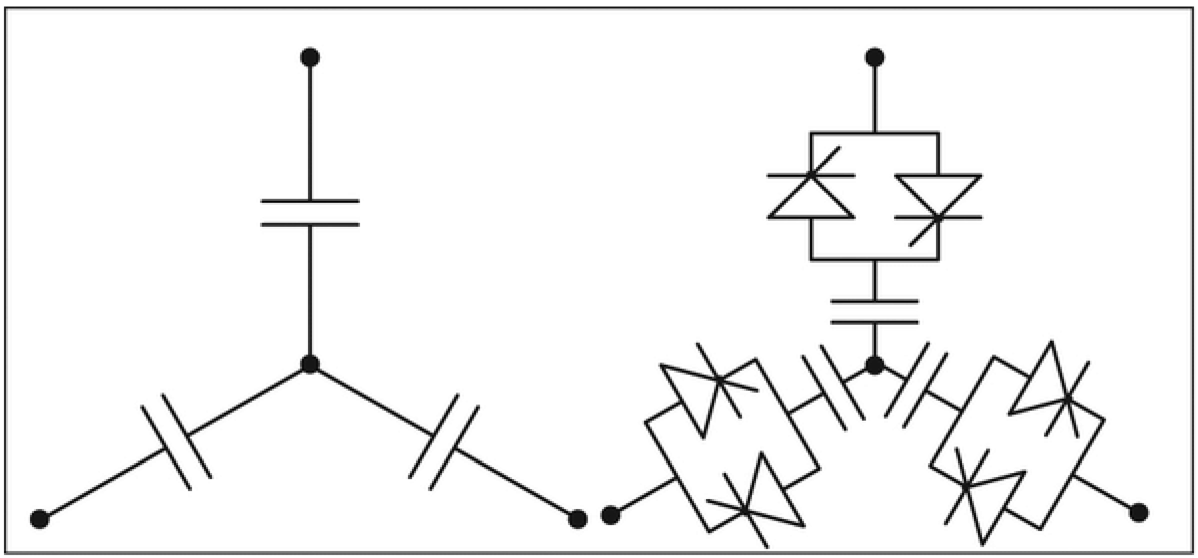


# AVR using STATCOM

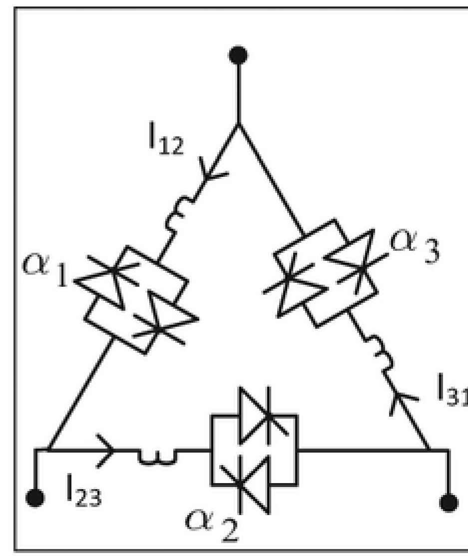
- **Static compensators – capacitor bank**

# AVR using STATCOM

FACTS compensators use either Thyristor switch capacitor (TSC) or Thyristor Controlled Reactor (TCR) with a fixed power factor correcting capacitor



Thyristor Switched Capacitor




Thyristor Controlled Reactor

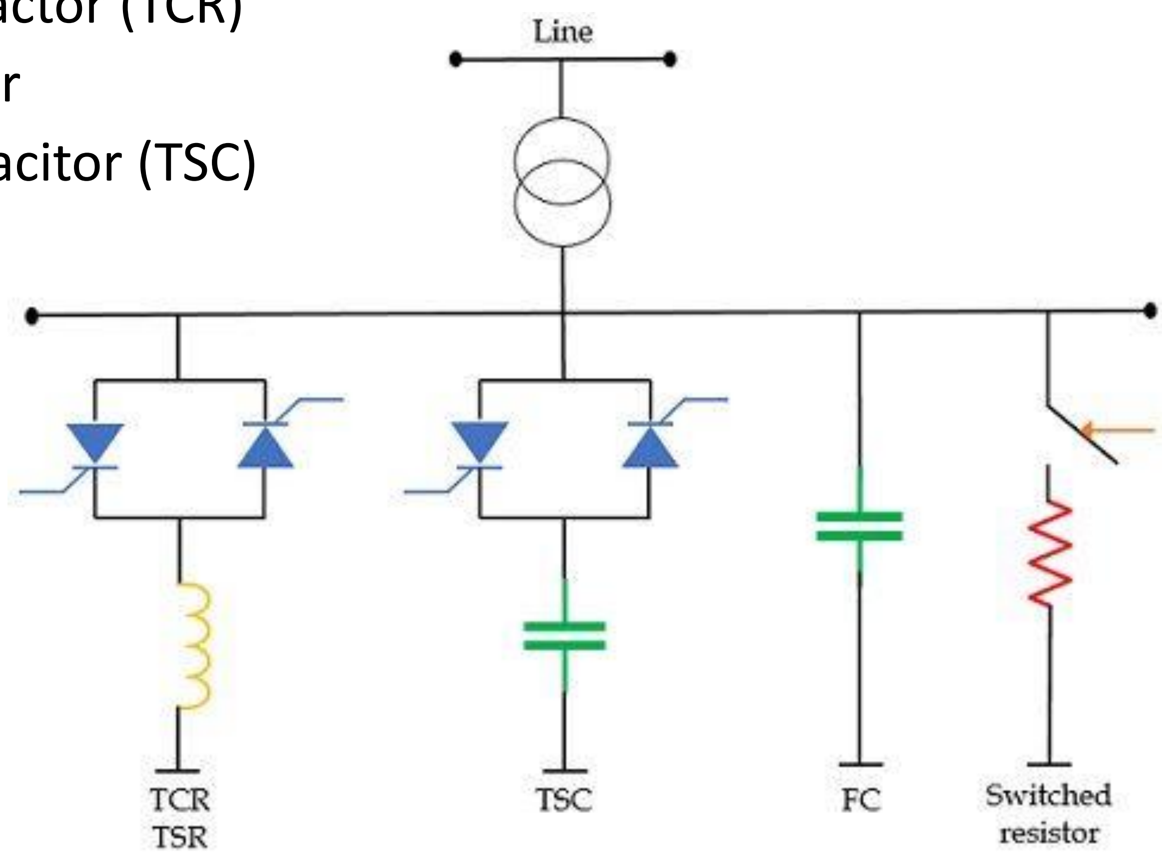
# AVR using STATCOM

Static VAR compensator (SVC) is such a FACTS device that is used to quickly control the voltage and reactive power of the terminal

SVC can be one of the following types:

- Thyristor controlled Reactor (TCR)
- TCR plus Fixed Capacitor
- Thyristor Switched Capacitor (TSC)
- TSC plus TCR

TSC plus TCR are very popular and most effective

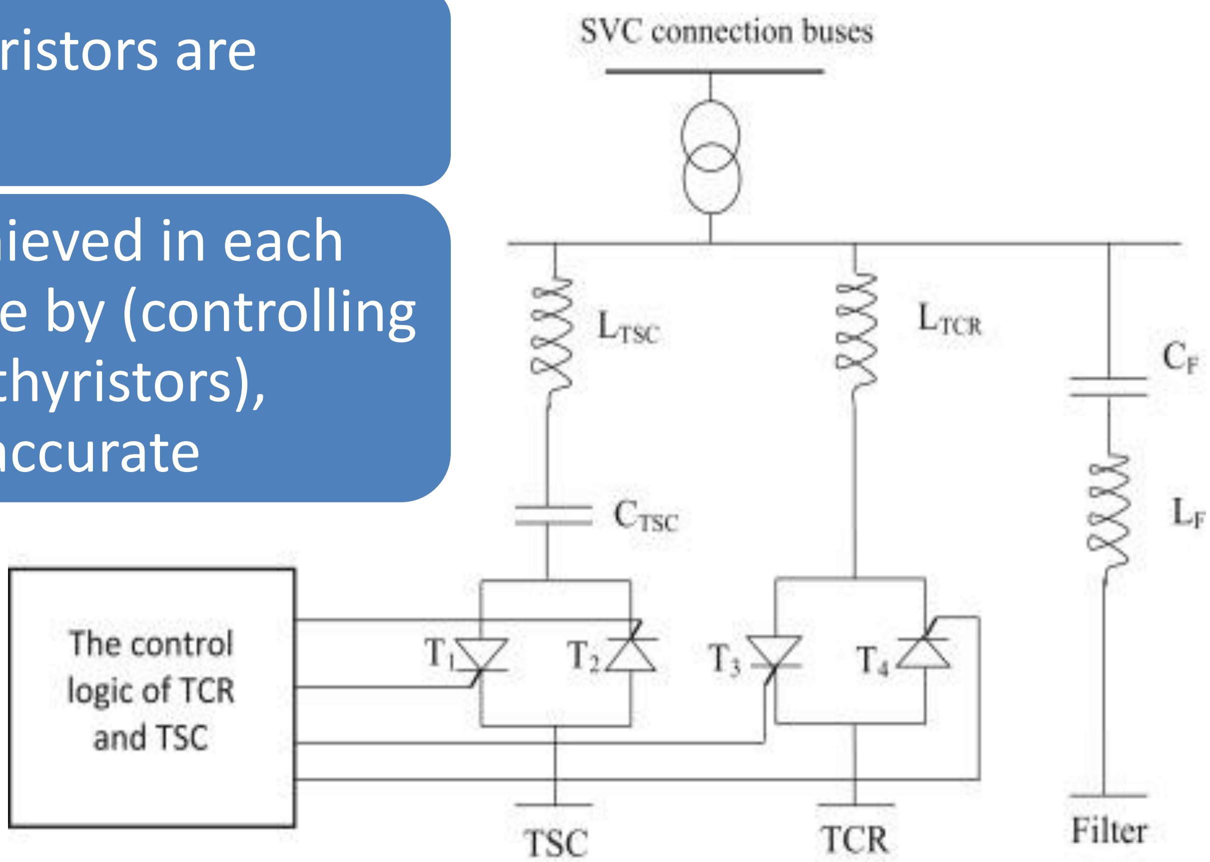


# AVR using STATCOM

The idea is to sense the voltage of the line and keep it stable by introducing capacitance or inductance in the circuit, depending on the signal generated by the Automatic Voltage Regulator (AVR)

The gating signals to thyristors are changed by AVR signal

Since control can be achieved in each cycle of the voltage wave by (controlling the conduction time of thyristors), control is very fast and accurate



# AVR using STATCOM

## Main objectives of SVC

- Correction of voltage regulation
- Reactive power control
- Improvement in system stability

## Advantages of SVC

- fast response
- Reliability
- low operating costs
- flexibility

# AVR using STATCOM

- **Static compensators - SVC**

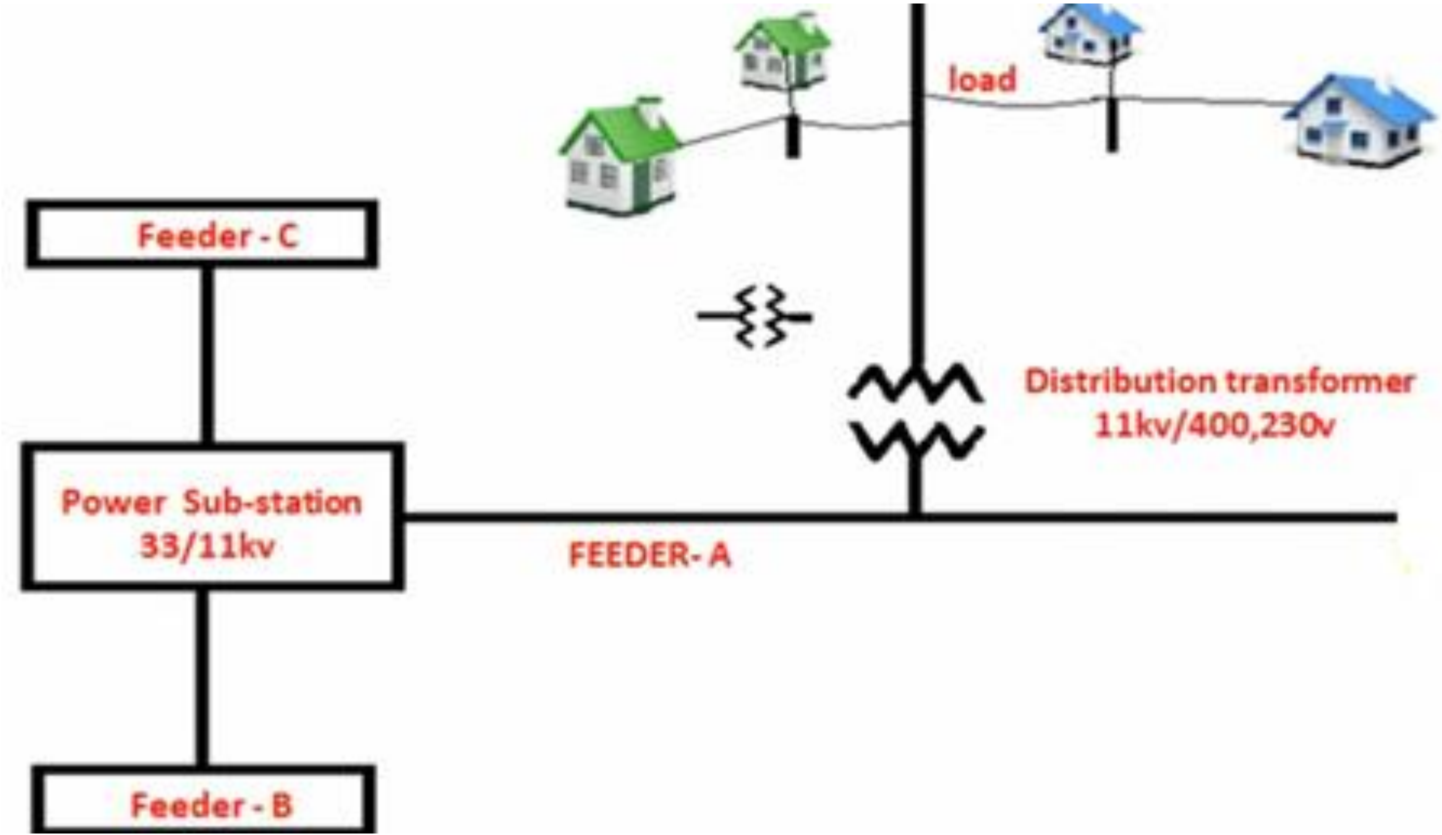
# AVR using STATCOM

- **Static compensators - SVC**

# AVR with Distributed Generation (DG)

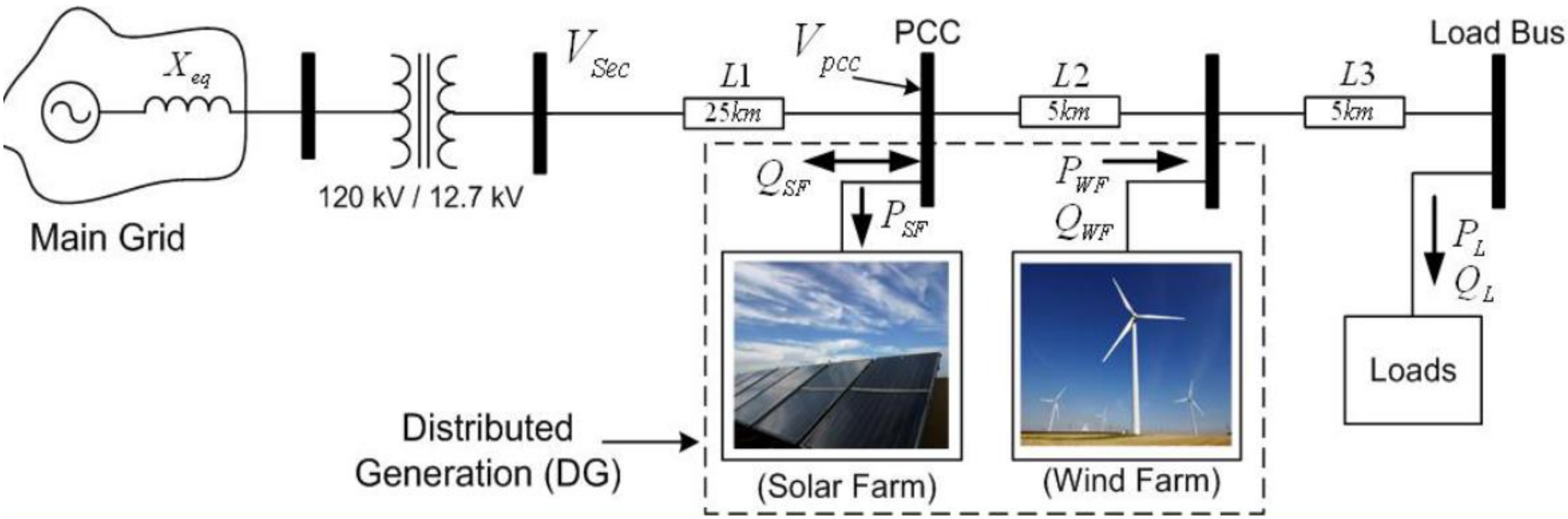
Usually, conventional power distribution networks have unidirectional power flow from the substation to customers

This leads to a descending voltage profile that leads to undervoltage near the load center



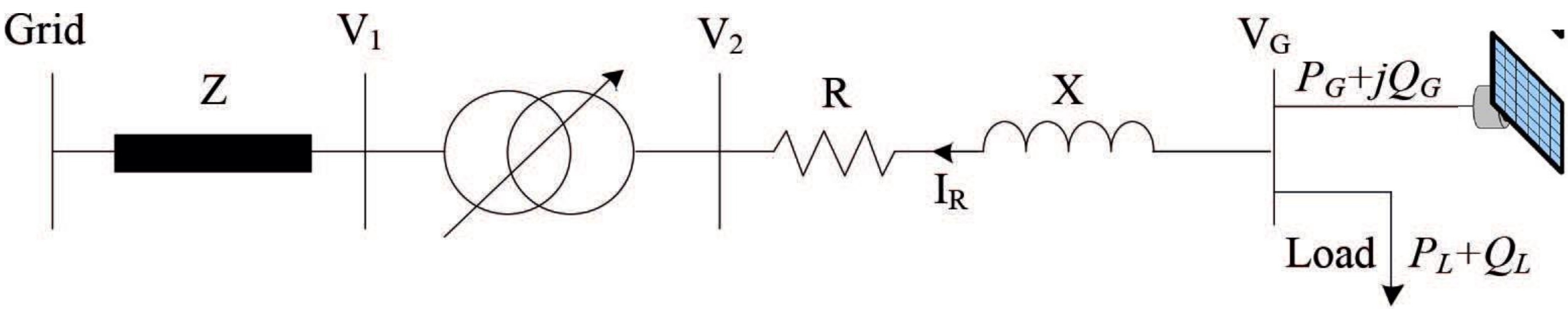
# AVR with DG

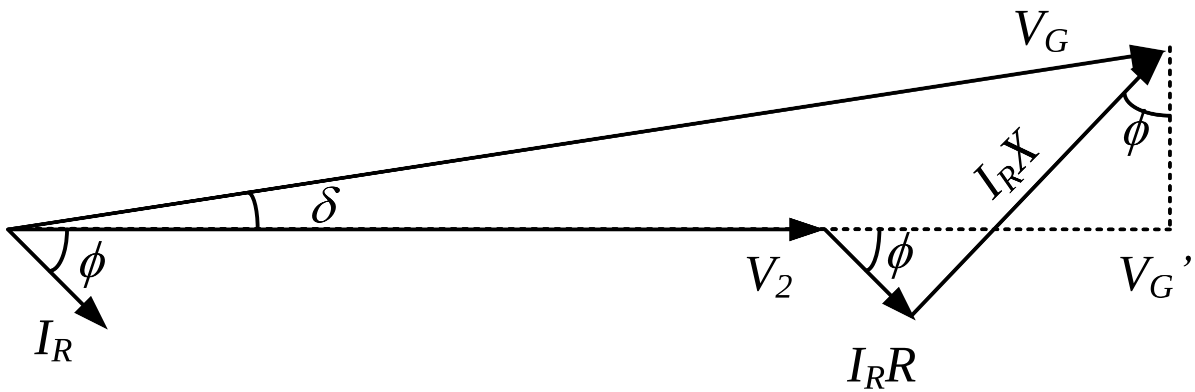
On the other hand, DG integration into distribution networks makes the power flow bi-directional; thus even an overvoltage problem may also occur



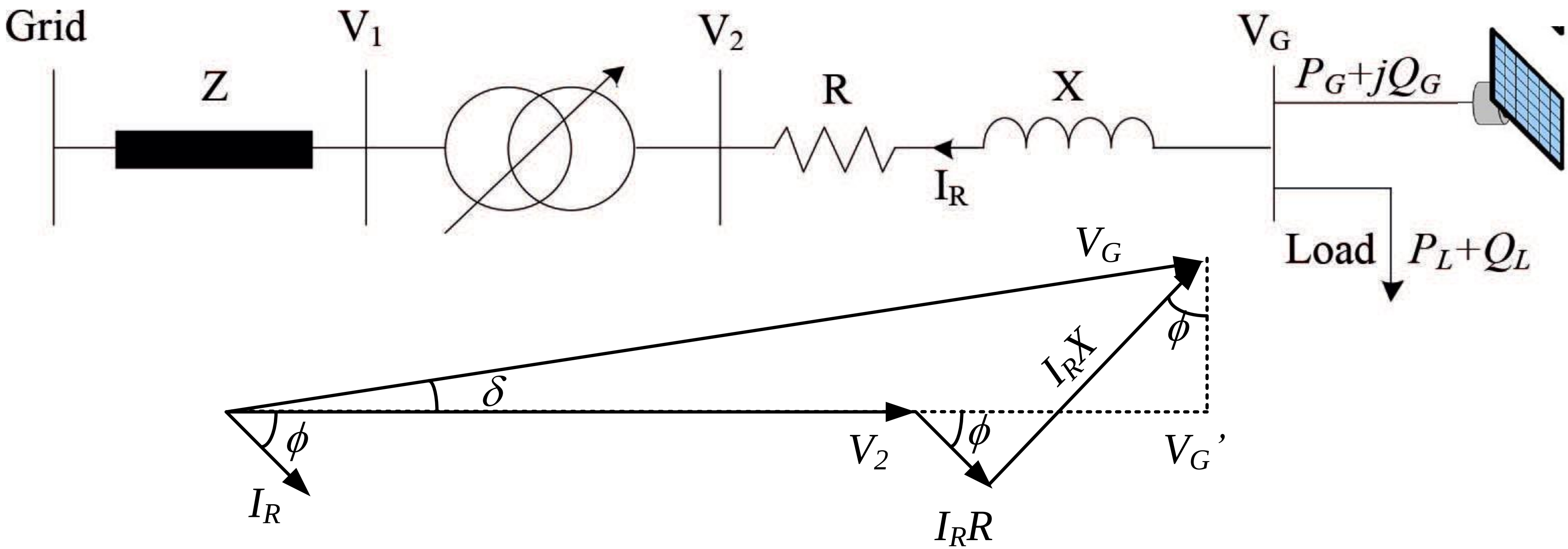
# AVR with DG

- A DG is connected at a load bus G
- $V_G$ is the DG output voltage



# AVR with DG

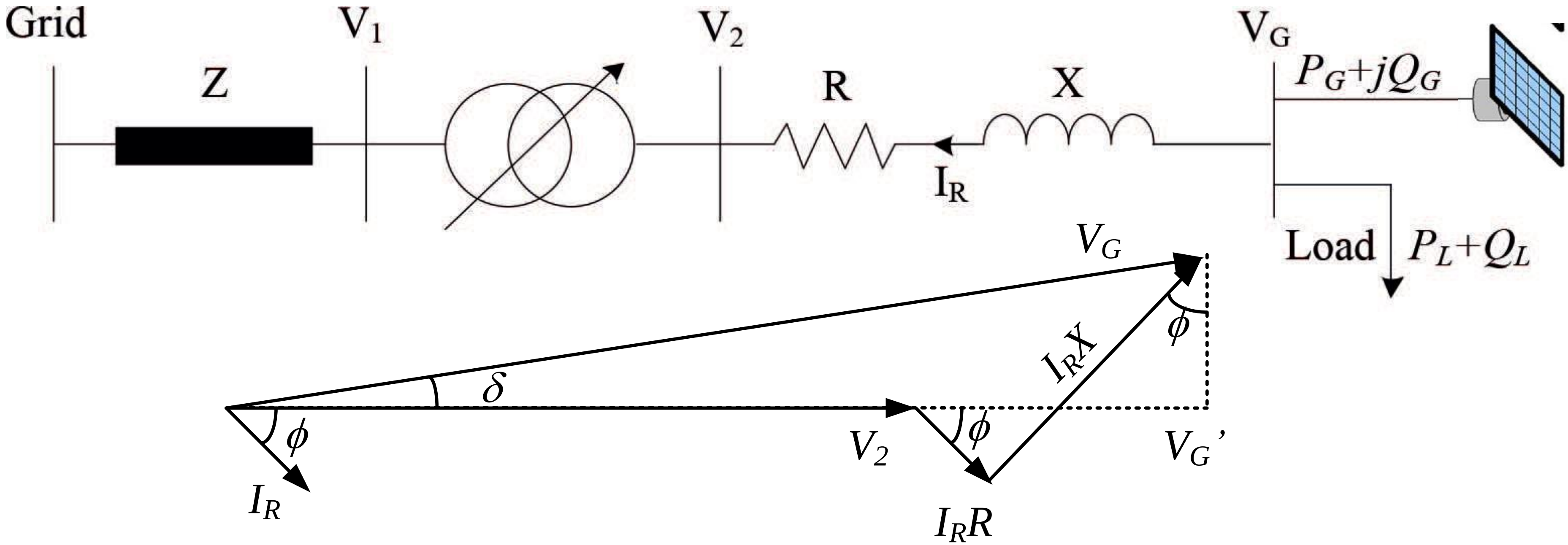



$$V_G' = |V_2 + I_R R cos\emptyset + I_R X sin\emptyset| \approx V_G cos\delta$$

The power angle (δ) is very small; hence the above can be approximated by

$$V_G' \approx V_G = V_2 + I_R R cos\emptyset + I_R X sin\emptyset$$

# AVR with DG




$$V'_G \approx V_G = V_2 + I_R R cos\emptyset + I_R X sin\emptyset$$

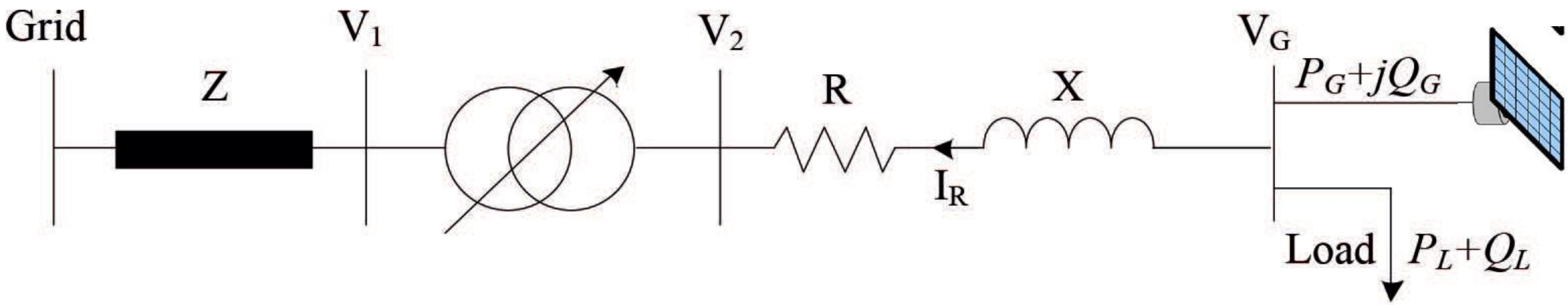
Therefore, the voltage rise caused by the DG, that is, $\Delta V_G = V_G - V_2$, is given by.

$$\nabla V_G = I_R R cos\emptyset + I_R X sin\emptyset$$

$$= \frac{V_G I_R cos\emptyset R}{V_G} + \frac{V_G I_R sin\emptyset X}{V_G}$$

$$= \frac{P_R R}{V_G} + \frac{Q_R \mathrm{x}}{V_G}$$

# AVR with DG



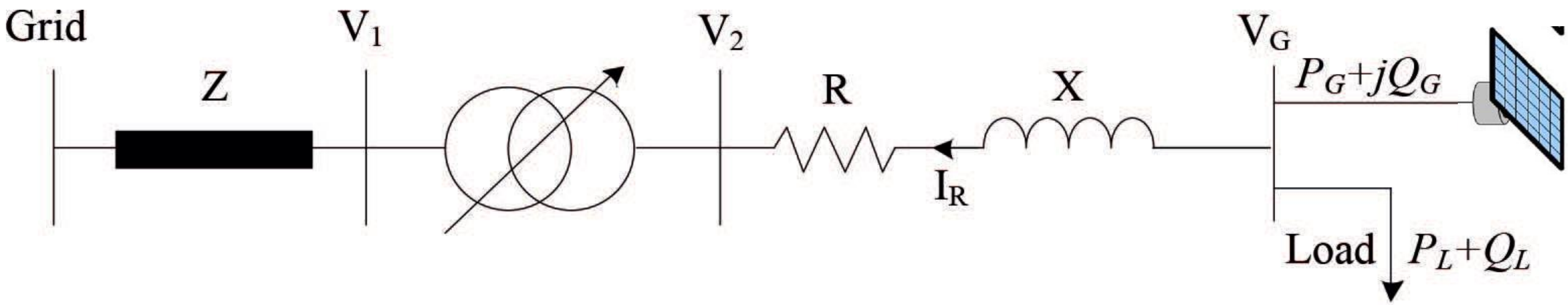

$$\nabla V_G = \frac{P_R R}{V_G} + \frac{Q_R \mathrm{x}}{V_G}$$

- where $P_R$ and $Q_R$ are the active and reactive powers that is fed back to the main grid $V_2$ from the DG and load bus $V_G$

$$\nabla V_G = \frac{(P_G - P_L)R}{V_G} + \frac{(Q_G - Q_L)\mathrm{x}}{V_G}$$

- where $P_G$ and $Q_G$ are the DG output active and reactive powers
- while $P_L$ and $Q_L$ are the load active and reactive powers

# AVR with DG

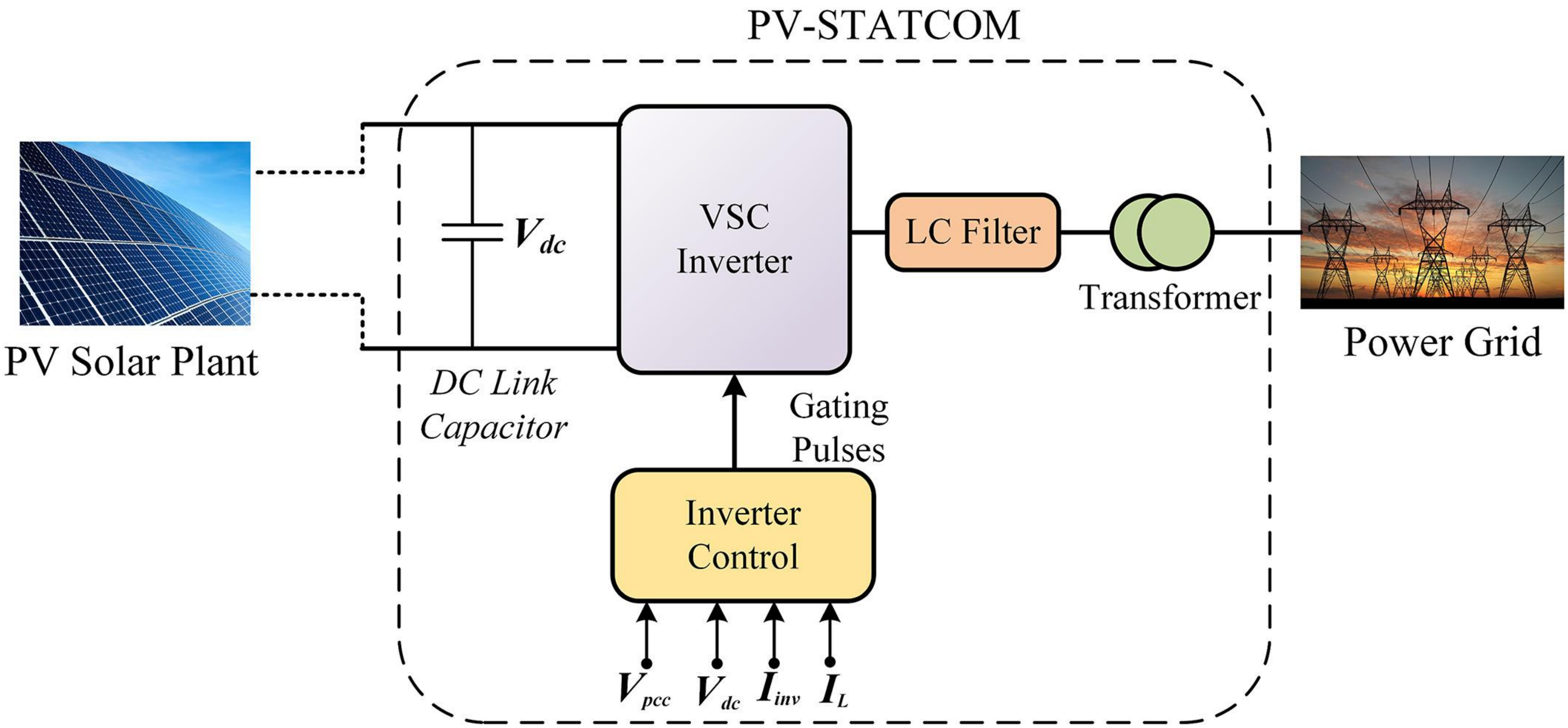



$$\nabla V_G = \frac{(P_G - P_L)R}{V_G} + \frac{(Q_G - Q_L)\mathrm{x}}{V_G}$$

- It can be seen that the highest overvoltage happens when the DG generates its maximum power during a light load condition (G > L)
- This problem is mainly associated with the excessive reverse power flow caused by the DG
- Increased integration of distributed energy resources on to the grid requires the inverter which can act as smart inverter by controlling active and reactive power, frequency control and regulation of voltage and power factor apart from its typical function of DC to AC conversion could be a potential solution

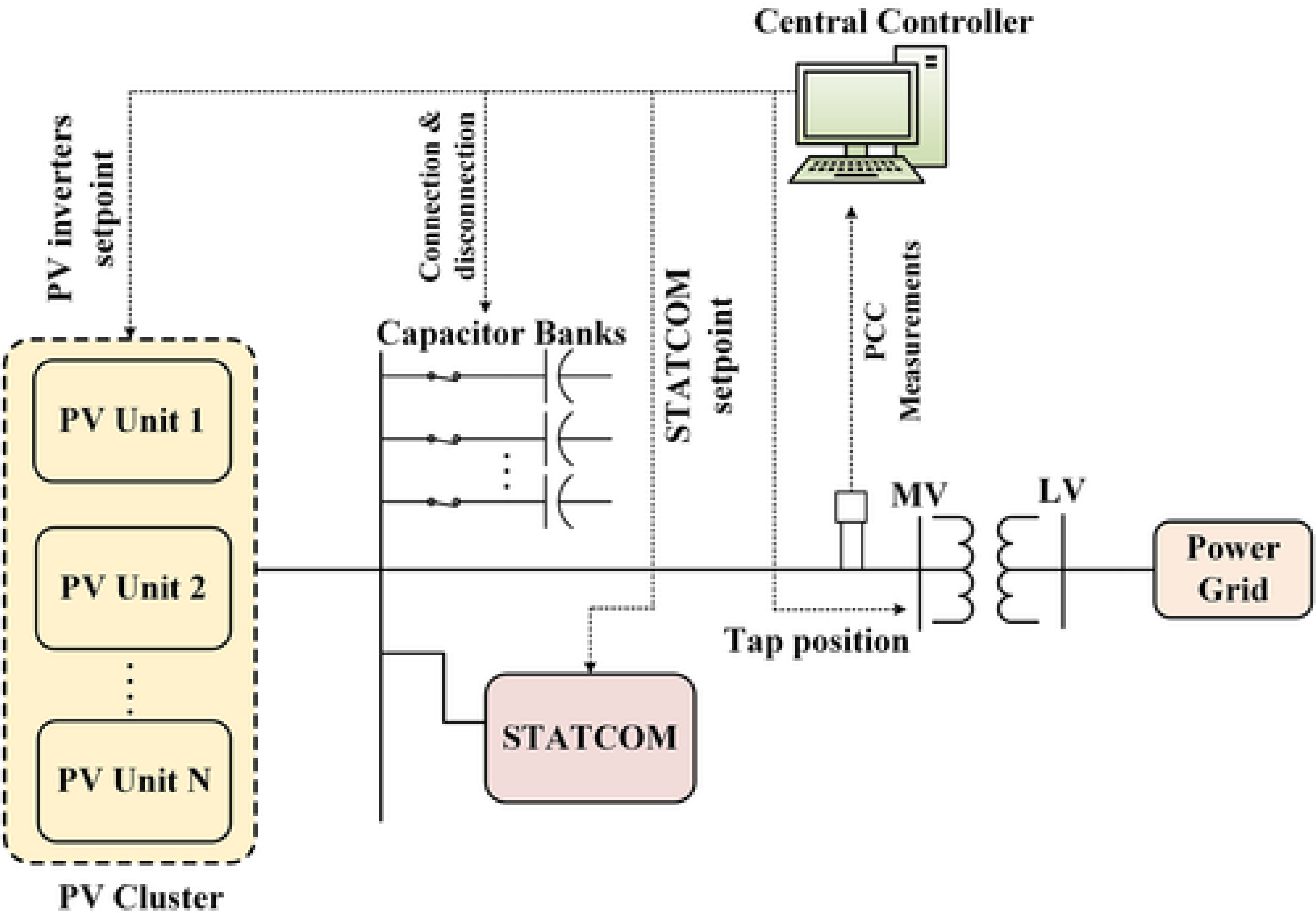
# AVR with DG

**Smart Inverter for DG integration**



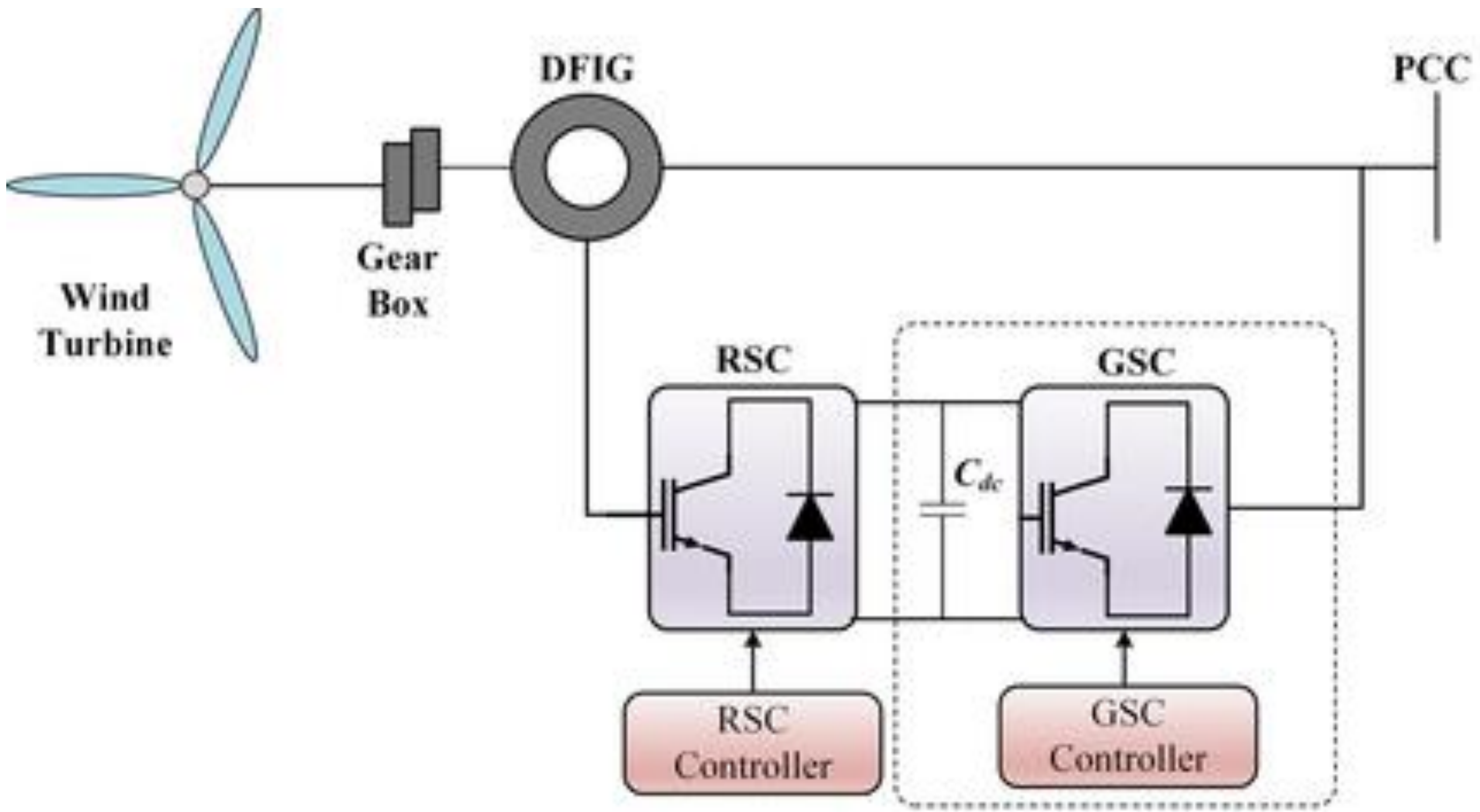
# AVR with DG

**Smart Inverter for DG integration**



# AVR with DG

**Smart Inverter for DG integration**



# AVR with Plug-in Electric Vehicles (PEV)

The growing penetration of plug-in electric vehicles (PEVs) can add high stress on voltage control devices due to the PEV stochastic and concentrated power profiles

Such power profiles may lead to high maintenance costs and reduced lifetimes for voltage control devices

These combined generation and load power profiles can lead to:

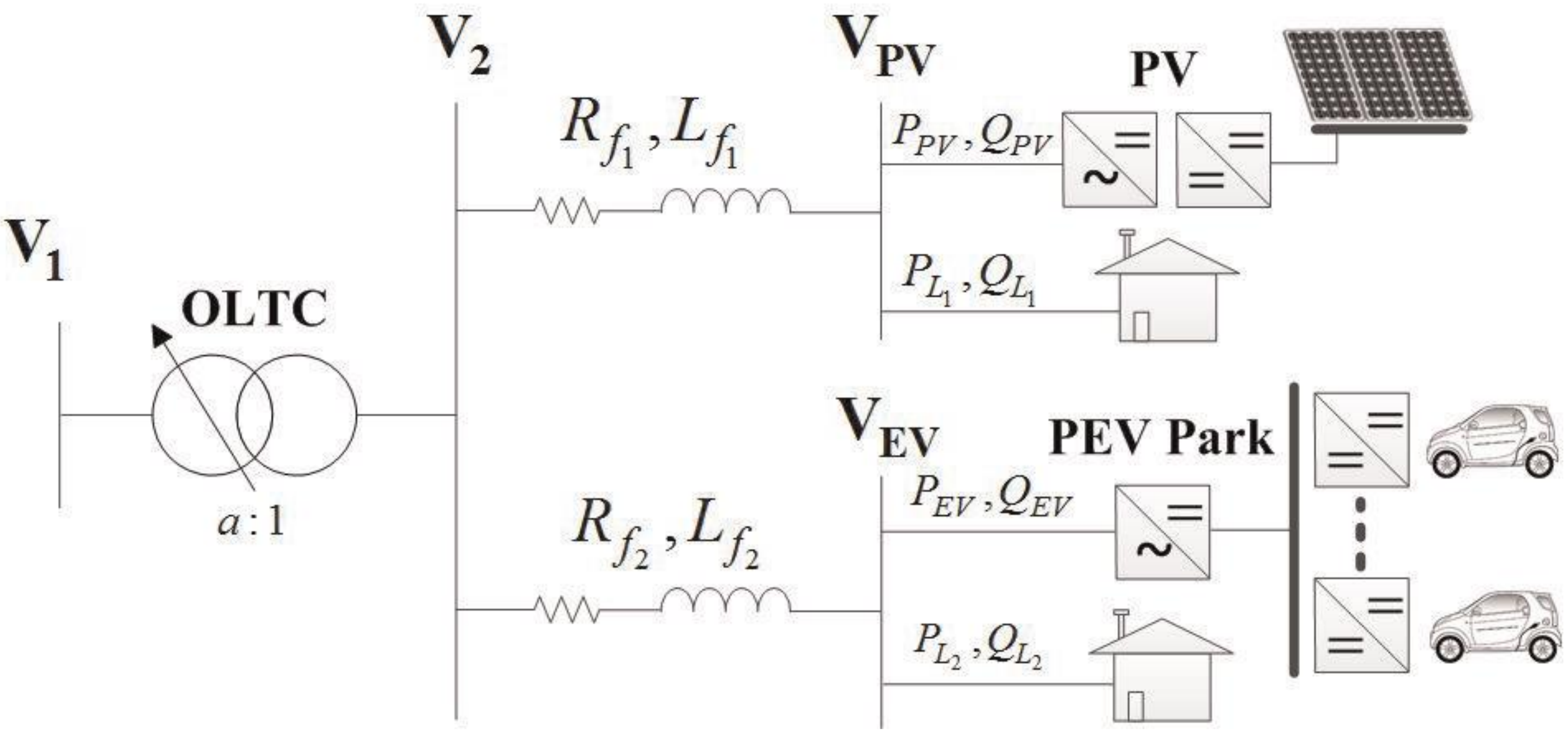
- over-voltages
- under-voltages
- high system losses

Thus limits on the integration of either PEVs or RES.

# AVR with PEV

Figure shows a simplified multi-feeder distribution network connected to a substation through an OLTC

The network has a photovoltaic (PV)-based DG and a PEV parking lot, which are connected at different feeder terminals

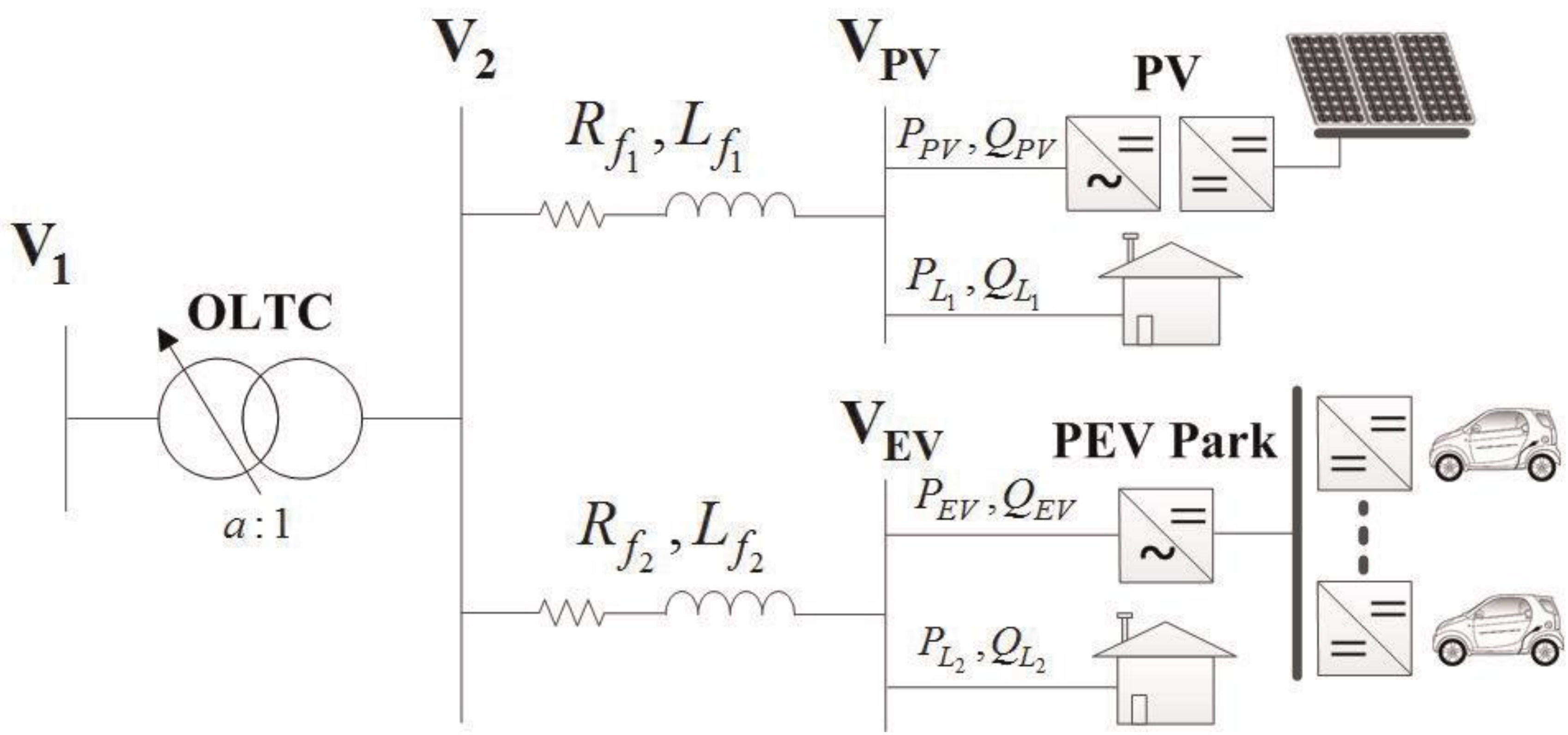


# AVR with PEV

- The voltage deviation for both DG and PEV (G2V) buses can be approximated by

$$\nabla V_{PV} = \frac{(P_{PV} - P_{L1})R_{f1}}{V_G} + \frac{(Q_{PV} - Q_{L1})X_{f1}}{V_G}$$

$$\nabla V_{EV} = \frac{-(P_{EV} + P_{L2})R_{f2}}{V_G} - \frac{(Q_{EV} + Q_{L2})X_{f2}}{V_G}$$



# AVR with PEV

$$\nabla V_{PV} = \frac{(P_{PV} - P_{L1})R_{f1}}{V_G} + \frac{(Q_{PV} - Q_{L1})X_{f1}}{V_G}$$

$$\nabla V_{EV} = \frac{-(P_{EV} + P_{L2})R_{f2}}{V_G} - \frac{(Q_{EV} + Q_{L2})X_{f2}}{V_G}$$

Equation shows that two worst-case scenarios may occur:

- Overvoltage - when the DG generates its maximum power during light loads and
- Undervoltage - during a peak load demand and low DG output

The integration of DGs and PEVs thus change the voltage profile significantly and complicates the voltage regulation

# AVR with PEV

This problem is due to two reasons:

- the voltage trend not descending from the substation to the feeder terminal, thereby invalidating the target point (reference)
- the voltage estimation, based on local measurements, becoming inaccurate because of the stochastic power natures of RES and PEVs

Therefore, OLTCs may suffer from wear and tear due to excessive operations

This problem worsens when one feeder suffers from overvoltage due to high DG penetration, while others suffer from undervoltage during high demand, such as PEV charging

In this instance, the OLTC will have two contradicting solutions

Increasing the transformer’s secondary voltage mitigates the undervoltage problem at the expense of the system’s overvoltage and vice versa

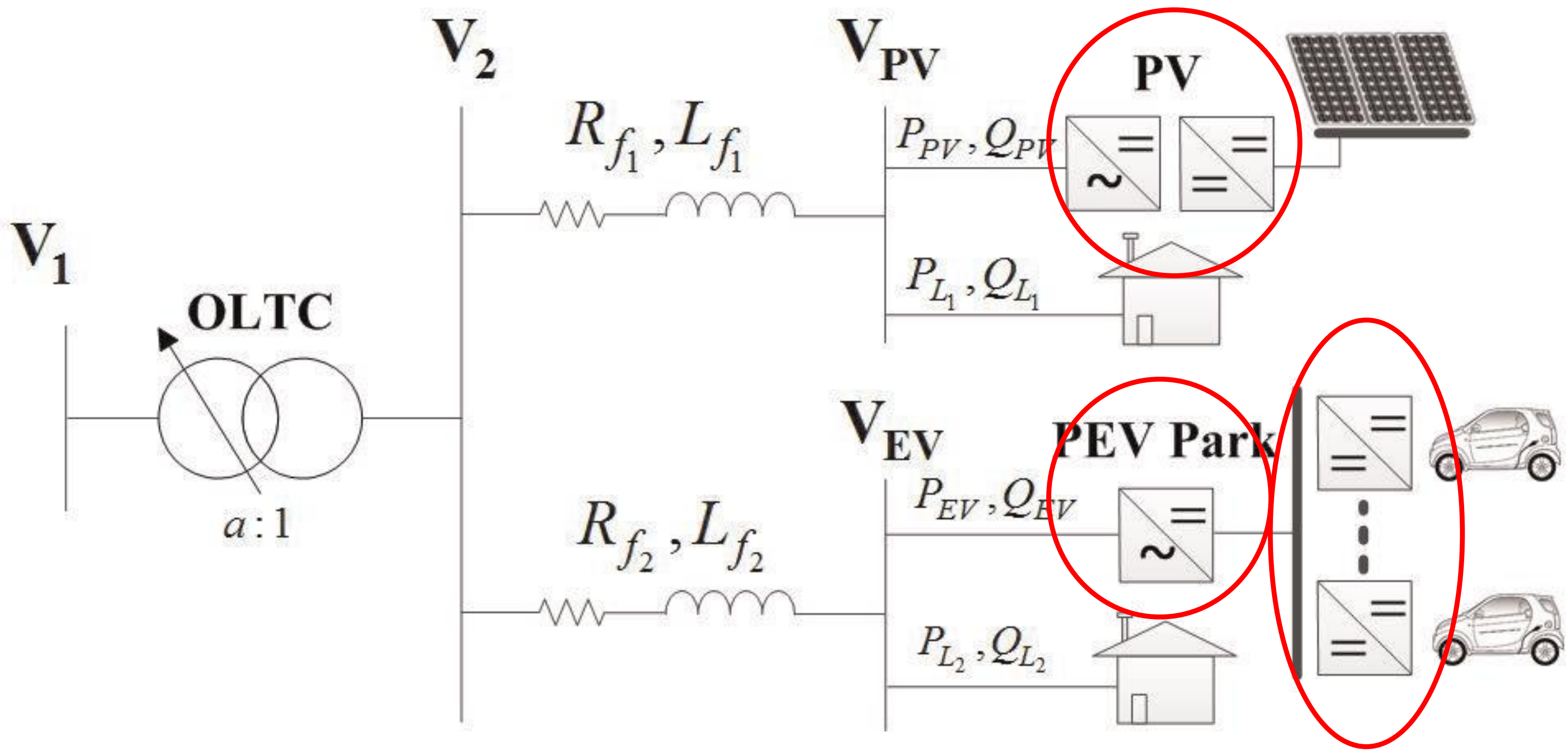
# AVR with PEV

A partial solution for this problem can be realized if a centralized-based controller for the OLTC uses the system's maximum and minimum voltages

However, this controller may not prevent the OLTC hunting problem during high PV power generation and peak EV demand, resulting in excessive tap operation

# AVR with PEV

For that reason, the power electronic converters that interface DGs and PEVs should be utilized in AVR operation



# AVR with PEV

The DG can support the voltage regulation through two options:

- absorbing reactive power and/or
- curtailment of active power

The first option is preferred since active power curtailment represents an energy waste

However, the capacity of the DG converter may limit the reactive power support and force the second option

To increase the reactive power support, the interfacing converter of the PEV can be employed to inject its surplus reactive power, thus reducing the DG active power curtailment

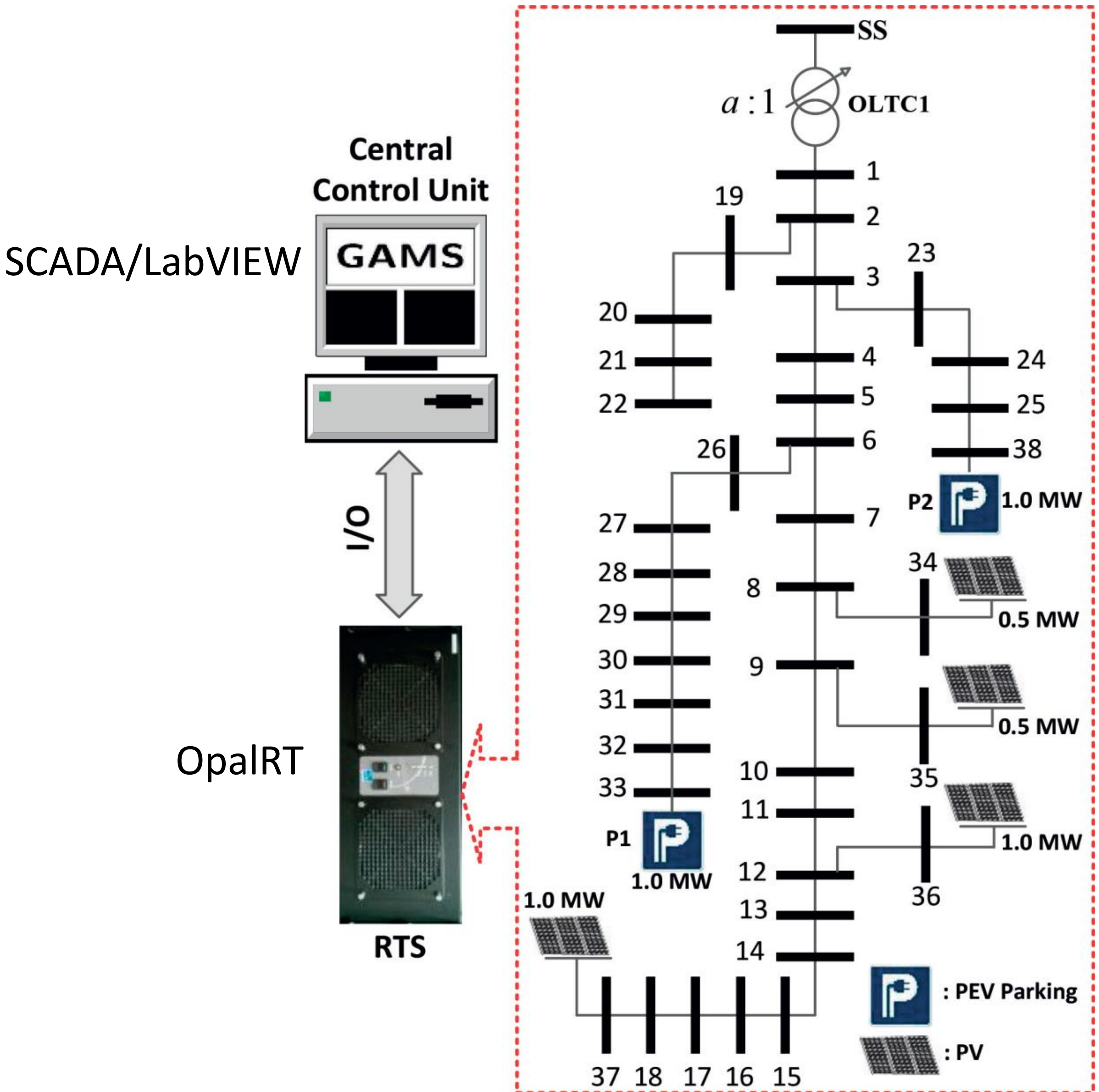
Thus, an optimal coordinated voltage regulation scheme is necessary to coordinate PEV, DG, and OLTC to achieve optimal voltage regulation and satisfy the self-objectives of each voltage control device

# AVR with PEV

## Optimal coordinated AVR Operation

- Both power electronic converters of PEVs and DGs can support the grid with reactive power to relax the OLTC.
- A vehicle-to-grid reactive power support (V2GQ) strategy can be adopted to incorporate PEVs and DGs in voltage regulation
- The main difference between vehicle-to-grid (V2G) strategies and the V2GQ is that the latter injects only reactive power to the grid
- Thus, it preserves the battery life of PEV, that is, the highest priority of the vehicles' owners
- The V2GQ comprises a three-stage nonlinear programming:
  - Stage (I) aims at maximizing the energy delivered to PEVs
  - Stage (II) minimizes the DG active power curtailment
  - Stage (III) minimizes the voltage deviations y Q support

# AVR with PEV


Central Control Unit
SCADA/LabVIEW
GAMS
I/O
OpalRT
RTS
SS
a : 1
OLTC1
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37
38
P1
1.0 MW
P2
1.0 MW
0.5 MW
0.5 MW
1.0 MW
1.0 MW
: PEV Parking
: PV

# AVR using Communication Network

Due to the intermittency of RES and PEVs, the conventional control schemes for OLTC and DGs fail to provide proper voltage regulation

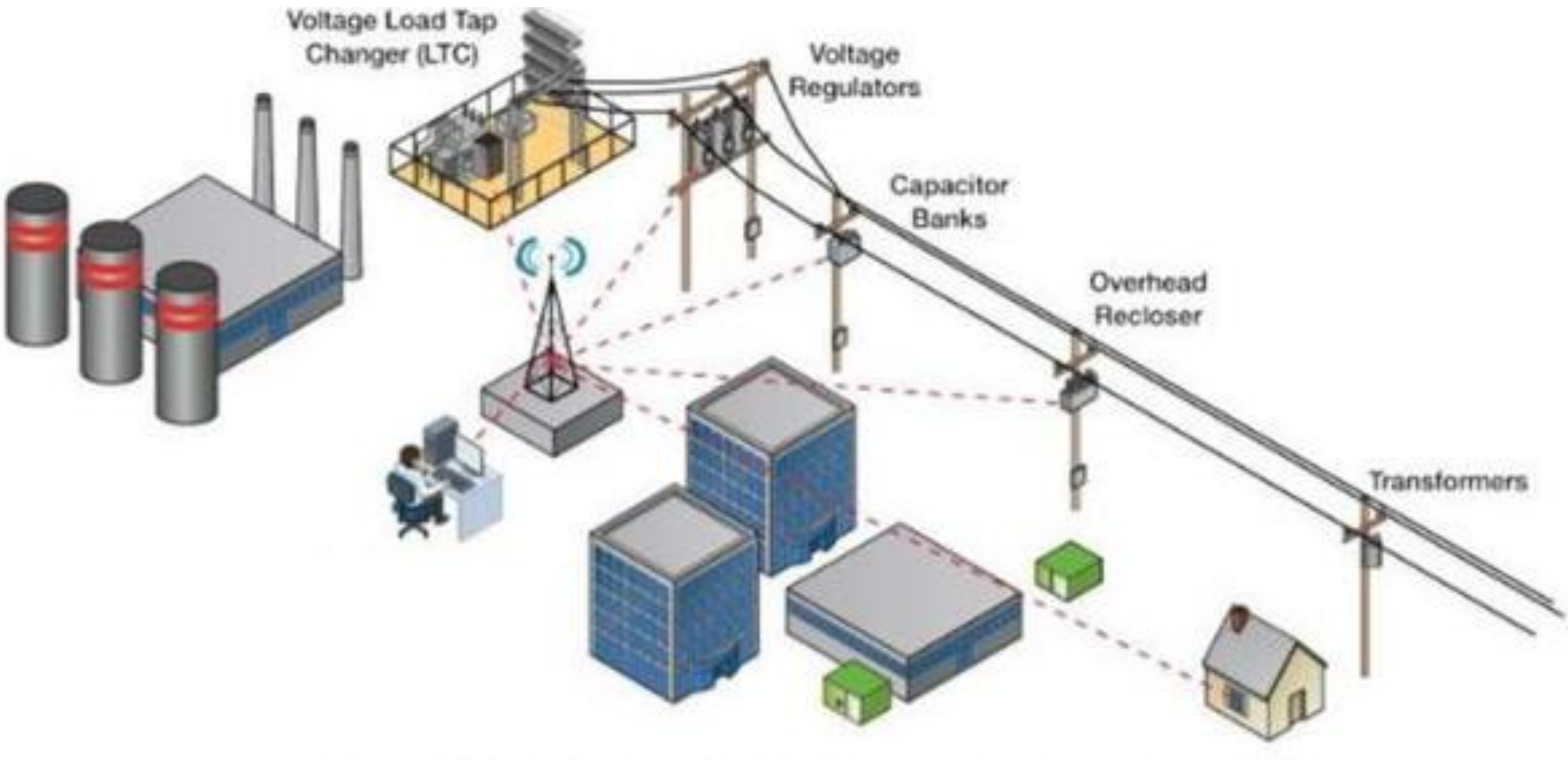
This shortcoming can be compensated using communication-assisted voltage regulation

The communication-assisted schemes fall under two approaches:

- distributed
- and centralized

Both approaches involve investment in communication links and remote terminal units

# AVR using Communication Network



# AVR using Communication Network

The distributed (intelligent) approach is an expert-based control, which coordinates a variety of voltage control devices with the goal of providing effective voltage regulation with fewer communication requirements

The centralized approach relies on a central point that monitors the system status and optimizes the operation of voltage control equipment

Typically, a centralized optimization problem is solved to dispatch the reactive power of different voltage control equipment based on:

- Load forecasting
- Generation monitoring