

VOLTAGE REGULATION OF THE DISTRIBUTION GRID

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Voltage Regulation and Power Quality Track
Monday and Tuesday Sessions



SESSION 6 – How DG Impacts Voltage Regulation.

What is DG

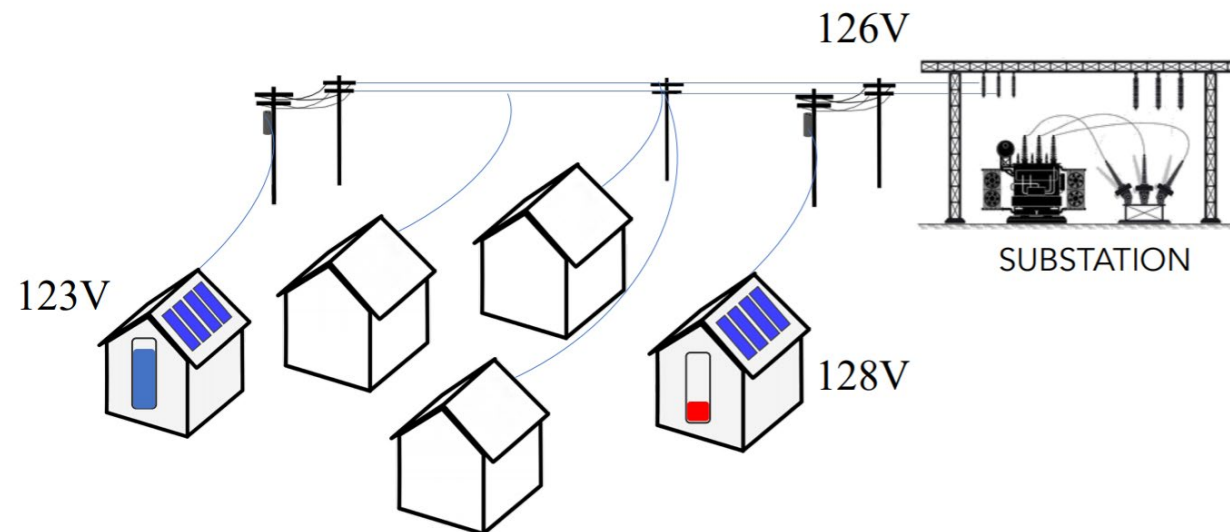
1. Distributed generation connected directly to the distribution grid:
 - a. Residential PV connected to the secondary network.
 - b. Utility Scale solar connected to the feeder.
 - c. Battery Storage connected either to the secondary or primary.
 - d. Small wind turbines connected to the secondary.
2. What do they have in common, Inverters.

What is the Problem Caused by DG

1. As mentioned earlier there is a voltage drop caused by the current flowing in the grid. The voltage at the source of the current is higher and the voltage drops as the current flows.
2. Typically, the substation is the source of the current and voltage drops from the substation to the end of the line.
3. DG is a current source and thus it causes a voltage rise as it injects current onto the circuit.
4. If the voltage gets too high the DG has to curtail output.

What is the Problem Caused by DG

1. One main obstacle in adding DG is the way the utilities currently operate the Grid.
2. By having bandcenters at 123-125 with bandwidths of 2-3 there is not enough headroom for the DG.



What is the Problem Caused by DG

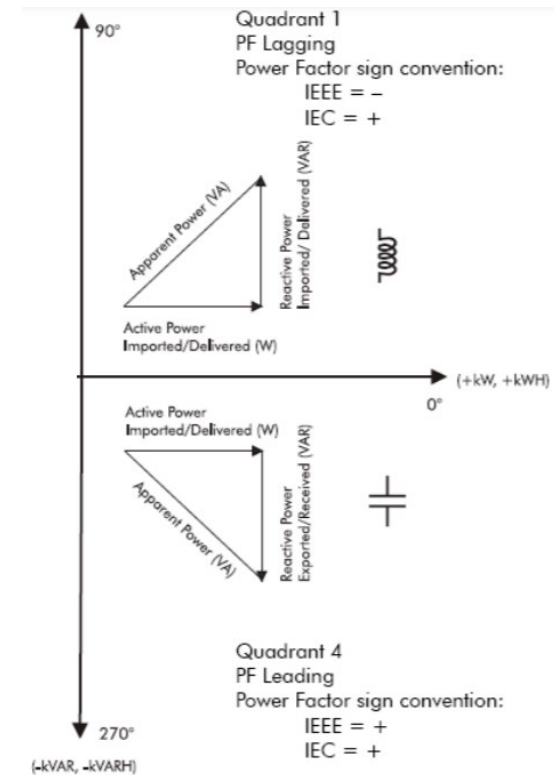
1. Once the DG has to curtail due to high voltage it can regulate the voltage down with the inverters in one of two manners:
 - a. Fixed pF – In this mode the inverters operate at fixed lagging pF. As they produce real current causing a voltage rise, they absorb reactive current to cause a voltage drop.
 - b. Volt/Var- Same concept, as the voltage goes up the inverters absorb Vars to bring the voltage back up.
 - c. Watt/Var – As the voltage goes up the inverter MW output is reduced.
2. If the inverters are operating at Unity pF once they reach the upper voltage limit they must curtail.

Smart Inverters – Fixed pF

How the Inverters Regulate the Voltage

1. The inverter is set to a fixed power.
2. Allowable limits are defined by the utility and are typically set at between 0.95 and 0.98 Lagging.
3. As the real power goes up so will the voltage so the inverters consumers Vars to bring the voltage back down.

Solar Farm Size	3 MW	3 MW
Fixed pF setting	0.98 lag	0.95 lag
KVAr Consumed at 25% output	152 KVAr	247 KVAr
KVAr Consumed at 50% output	305 KVAr	493 KVAr
KVAr Consumed at 75% output	457 KVAr	740 KVAr
KVAr Consumed at 100% output	609 KVAr	986 KVAr
Solar Farm Size	5 MW	5 MW
Fixed pF setting	0.98 lag	0.95 lag
KVAr Consumed at 25% output	254 KVAr	411 KVAr
KVAr Consumed at 50% output	508 KVAr	822 KVAr
KVAr Consumed at 75% output	761 KVAr	1233 KVAr
KVAr Consumed at 100% output	1015 KVAr	1643 KVAr



Smart Inverters – Volt - Var

How the Inverters Regulate the Voltage

1. Typical Inverter Volt/Var curve. When the voltage is in band it operates at unity pF.
2. When the Voltage is High the inverter sinks Vars to lower the voltage and when the voltage is low the inverter sources Vars to raise the voltage.

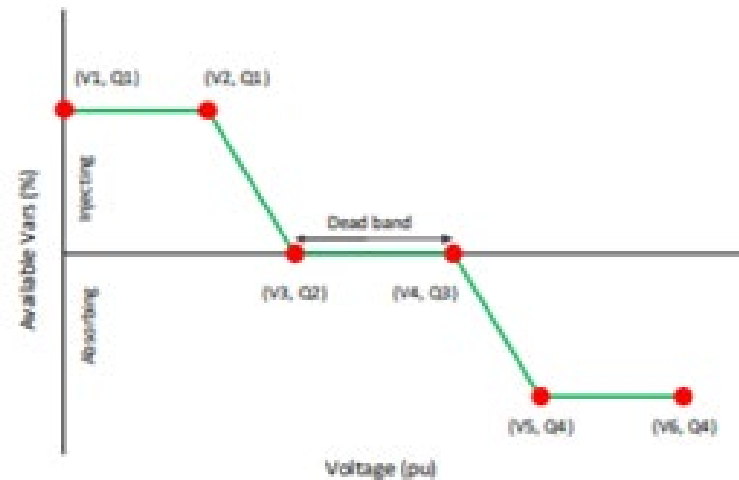


Figure 1. Volt/var curve

Smart Inverters – Volt - Var

How the Inverters Regulate the Voltage

1. The higher the voltage is on the circuit pre-DG the more aggressive the inverters will be and therefore the more they will impact the pF of the circuit. Circuits can become Var deficient (need more cap banks). The inverter will be typically oversized so that it can put out the maximum Var limit while maintaining the Maximum MW.

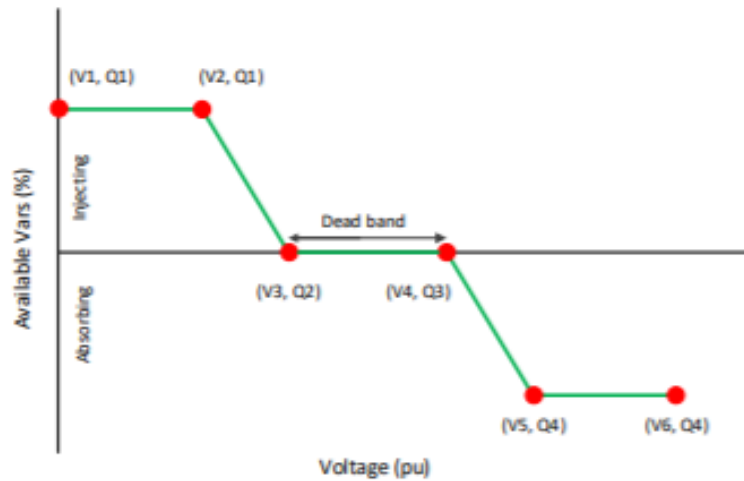


Figure 1. Volt/var curve

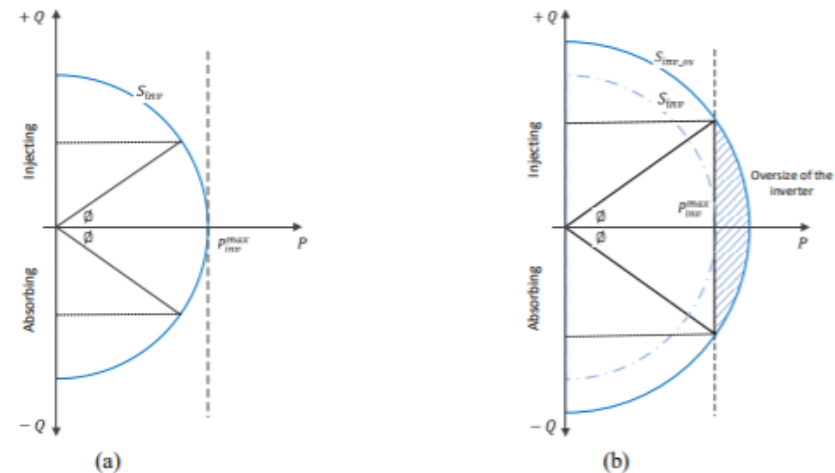


Figure 2. PV inverter capability curve, (a) Typical inverter, (b) Oversized inverter

Smart Inverters – Volt - Var

How the Inverters Regulate the Voltage

1. In this example if the voltage is between 0.96 pu and 1.04 pu the inverter operates at unity pF.
2. At 1.04 pu the inverter starts to consume Vars and at 1.06 pu it is consuming maximum Vars.

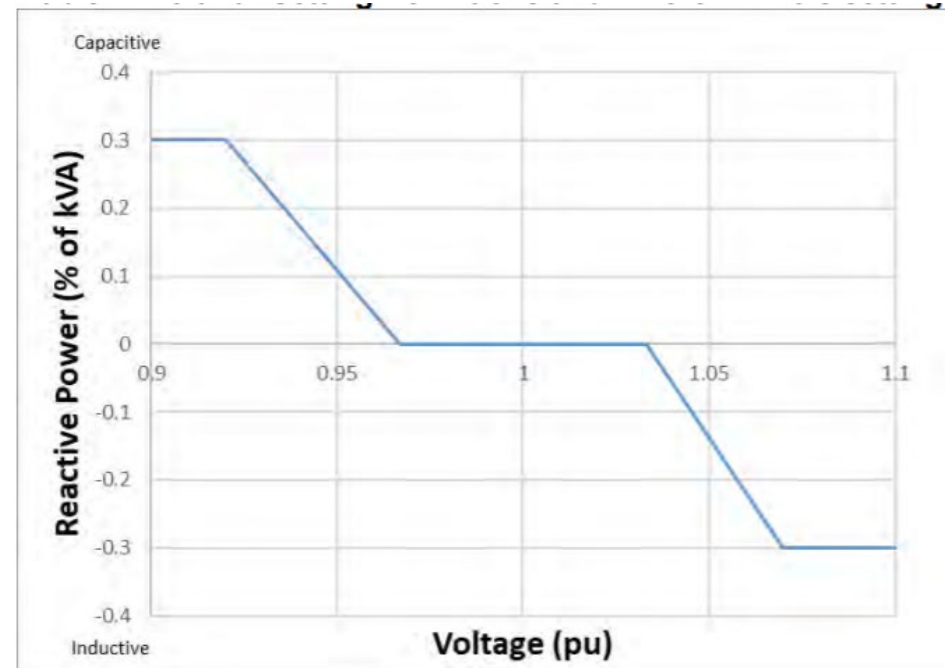


Fig 2: Ameren Illinois' Approved Volt-var Setting

Smart Inverters – Volt - Var

How the Inverters Regulate the Voltage

1. At Ameren, this feeder is having the inverters at the two DG sites consume over 700 KVAR.

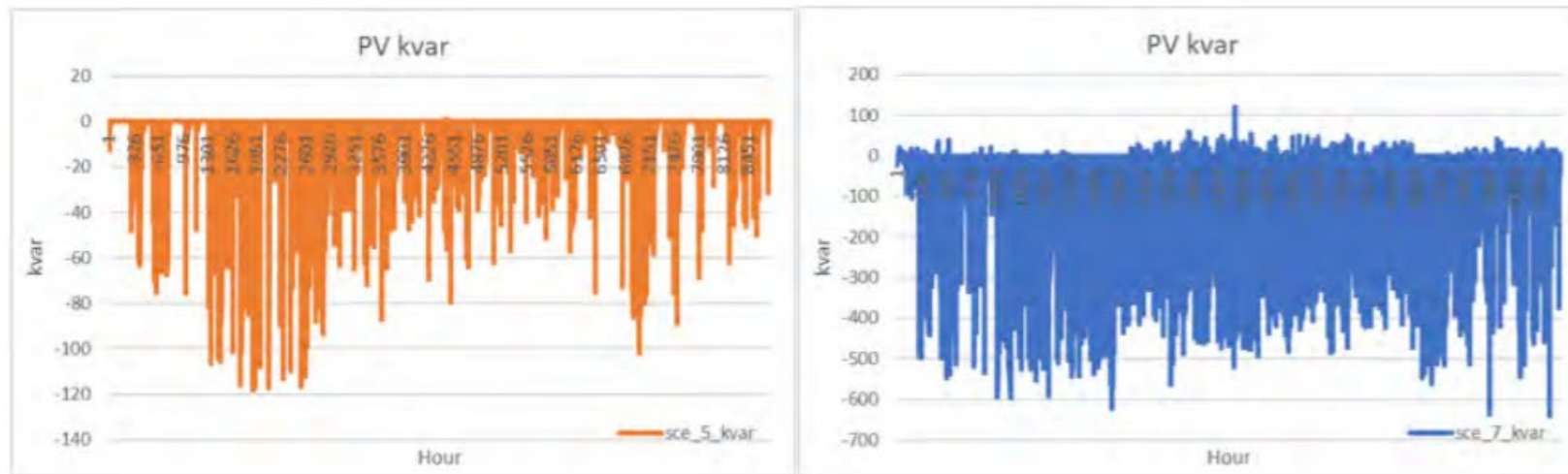


Fig.41: Total Reactive Power Output for Feeder Q85162

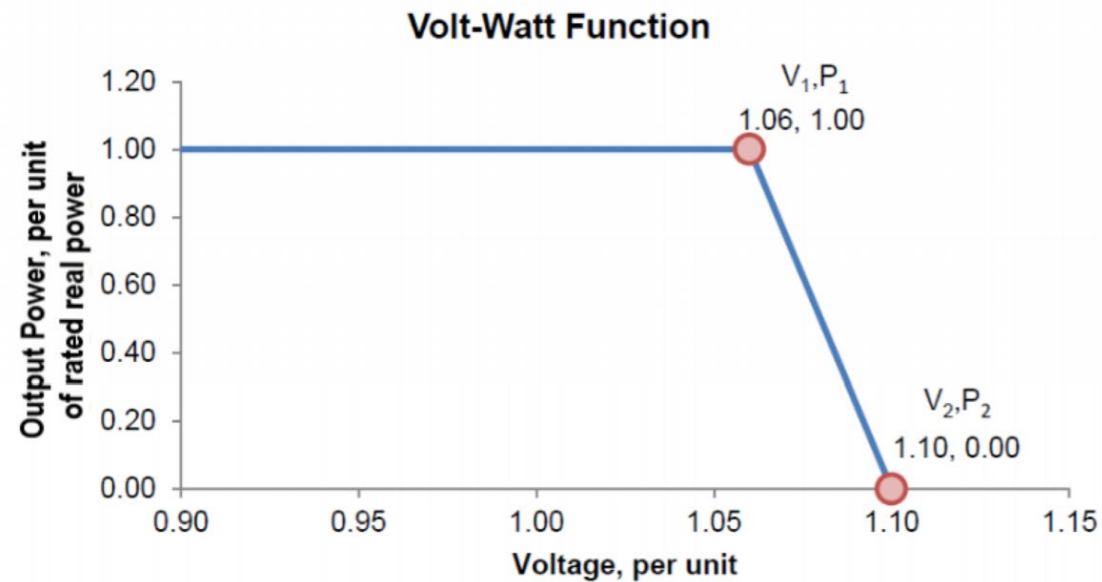
Circuit	Phase 1 Type	Residential Added Solar (MW)	Non-Residential Added Solar (MW)	Community Added Solar (MW)
P73182	Community Solar	1.23	2.50	2.00
Q85162	Community Solar	2.24	2.35	2.00
N70330	Non-Residential	1.95	2.54	2.00
V23522	Non-Residential	0.73	1.51	2.00
K39153	Non-Residential	1.96	3.38	2.00
Y98532	Non-Residential	0.56	1.99	2.00
N95824	Non-Residential	0.96	1.66	2.00
D89002	Residential	3.01	0.64	2.00
L23145	Residential	1.86	1.34	2.00
Q16867	Residential	2.67	1.17	2.00

Table 3: Phase 1 PV Placement

Smart Inverters – Volt - Watt

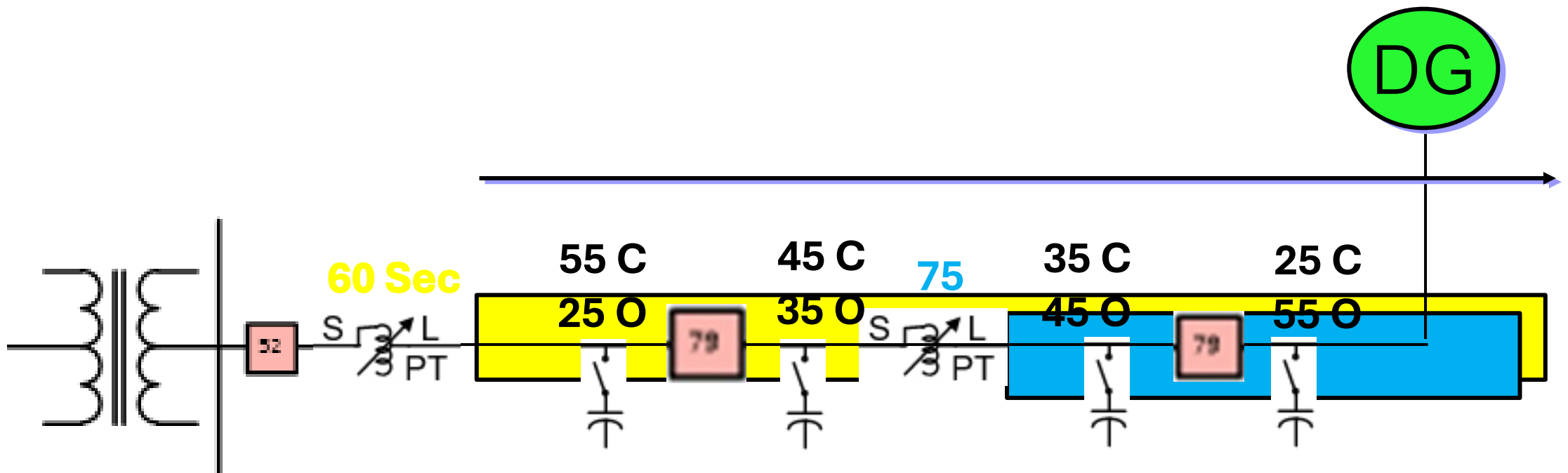
How the Inverters Regulate the Voltage

1. The inverter start to curtail real power as the voltage increases and must trip off if the voltage exceeds an upper setting.
2. Utilities like it but developers don't because of the loss in revenue.



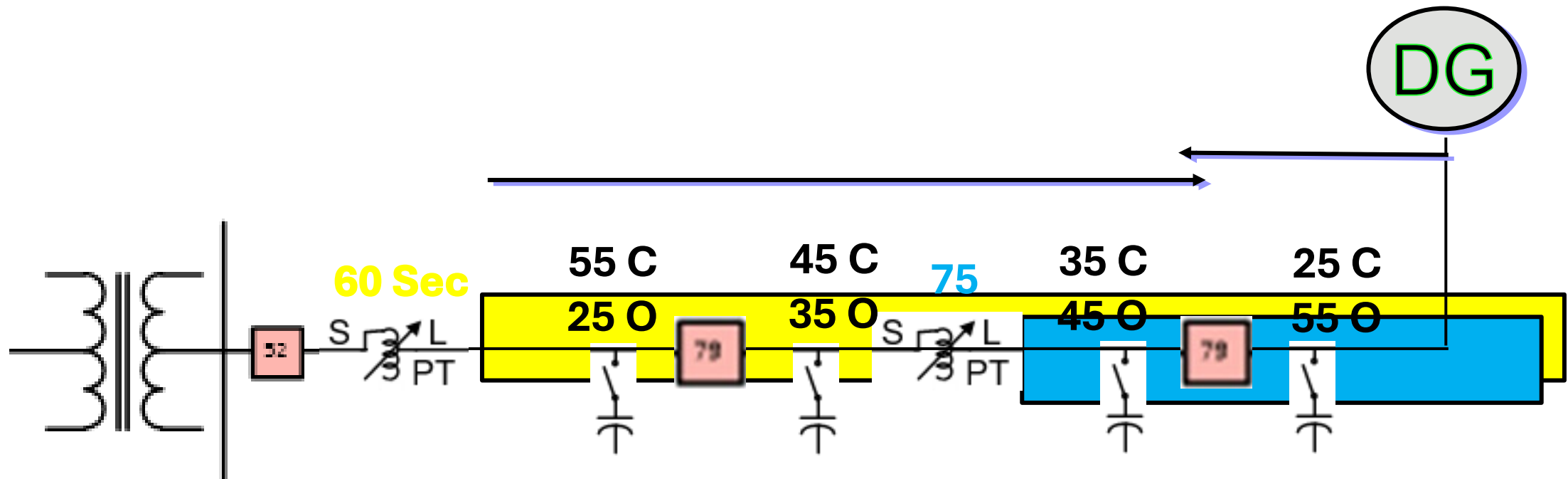
Typical Feeder with Utility Solar

1. This is a typical feeder with regulators and capacitors that are coordinated and the capacitors are voltage controlled. There is a DG on the circuit but it is not producing power.
2. The Voltage controlled capacitor banks are probably closed to prop up the EOL voltage.



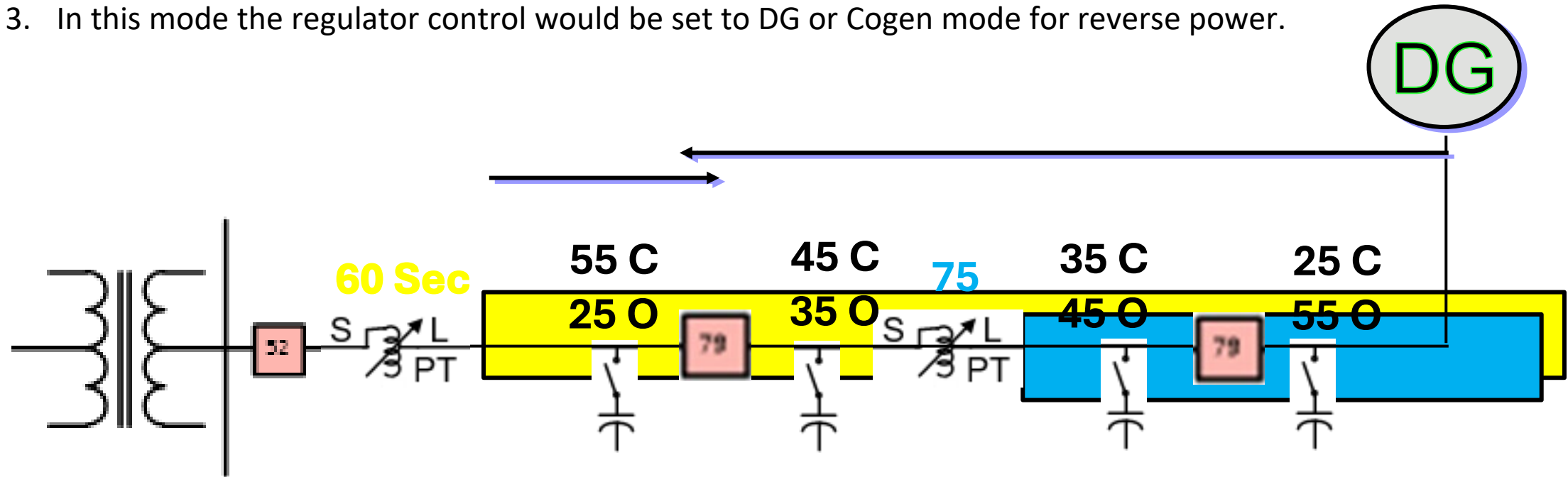
Typical Feeder with Utility Solar

1. The DG starts producing some power in the morning but not enough to have the regulator go into reverse power. The regulator just see the load go down as some of it is being served on its load side. The voltage at the DG site start to climb.
2. As the voltage starts to climb at the EOL the furthest capacitor bank opens up to drop the voltage.
3. With the loss of the cap bank the circuit starts to go lagging.



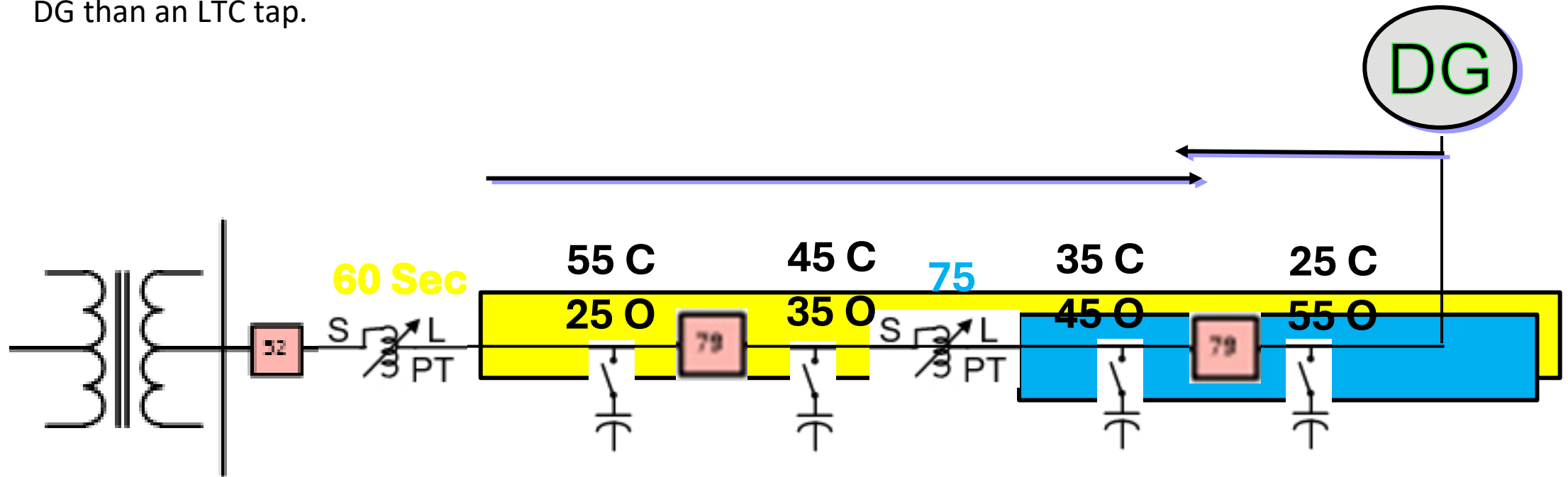
Typical Feeder with Utility Solar - Regulators

1. The regulator is in reverse power but the substation source is still on the source side of the regulator, the sensing voltage is still on the load side and it is still regulating the same portion of the circuit.
2. If LDC is used, the regulator control may require different R and X settings in reverse as positive current causes the regulator to raise the voltage while negative current causes it to lower the voltage.
3. In this mode the regulator control would be set to DG or Cogen mode for reverse power.



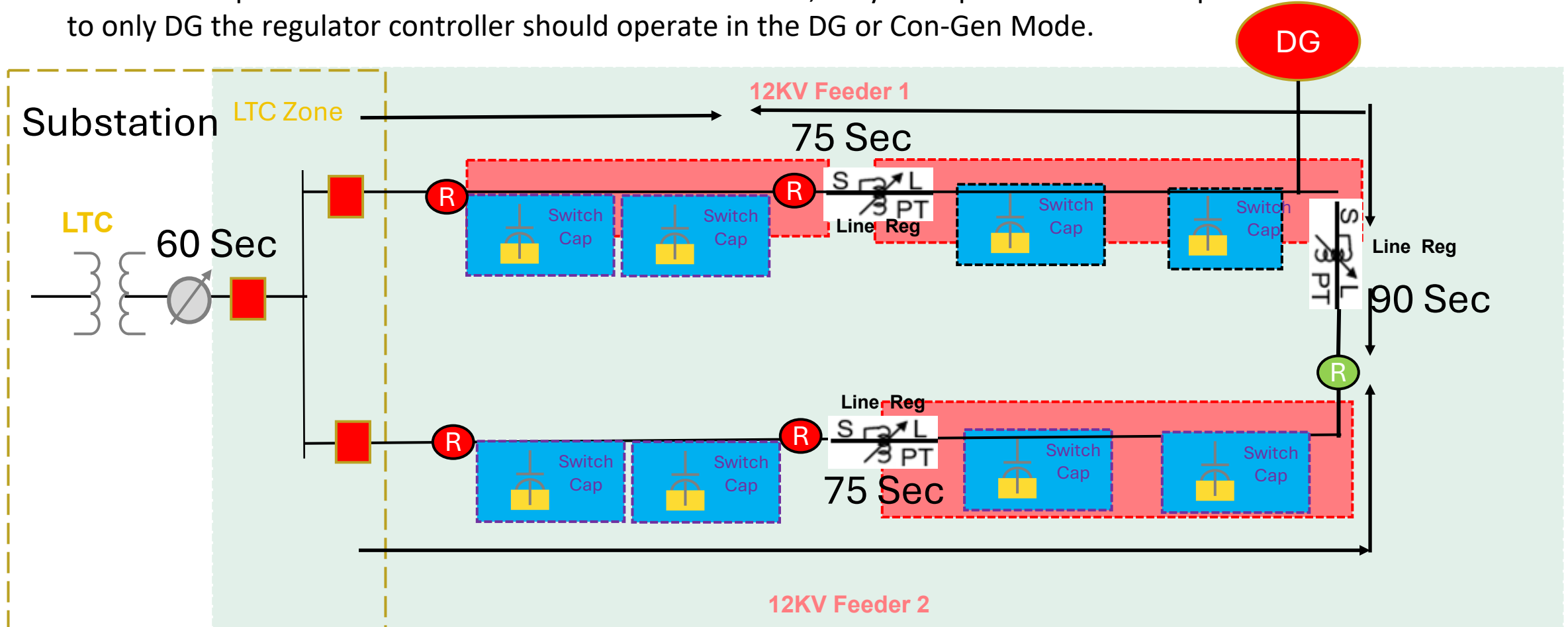
Typical Feeder with Utility Solar - Capacitors

1. The capacitor banks will be off, at least at the EOL due to the voltage rise caused by the DG.
2. The DG inverter is consuming VARs to bring the voltage down.
3. The circuit is now Var deprived and Vars will be following through the substation transformer.
4. This will cause the substation LTC to operate which will raise the voltage on the entire feeder, causing the inverter to require additional Vars.
5. The solution is to have the cap bank closest to the source converted to Var control. It can provide the Vars and keep the substation bus voltage up while creating less voltage rise at the DG than an LTC tap.



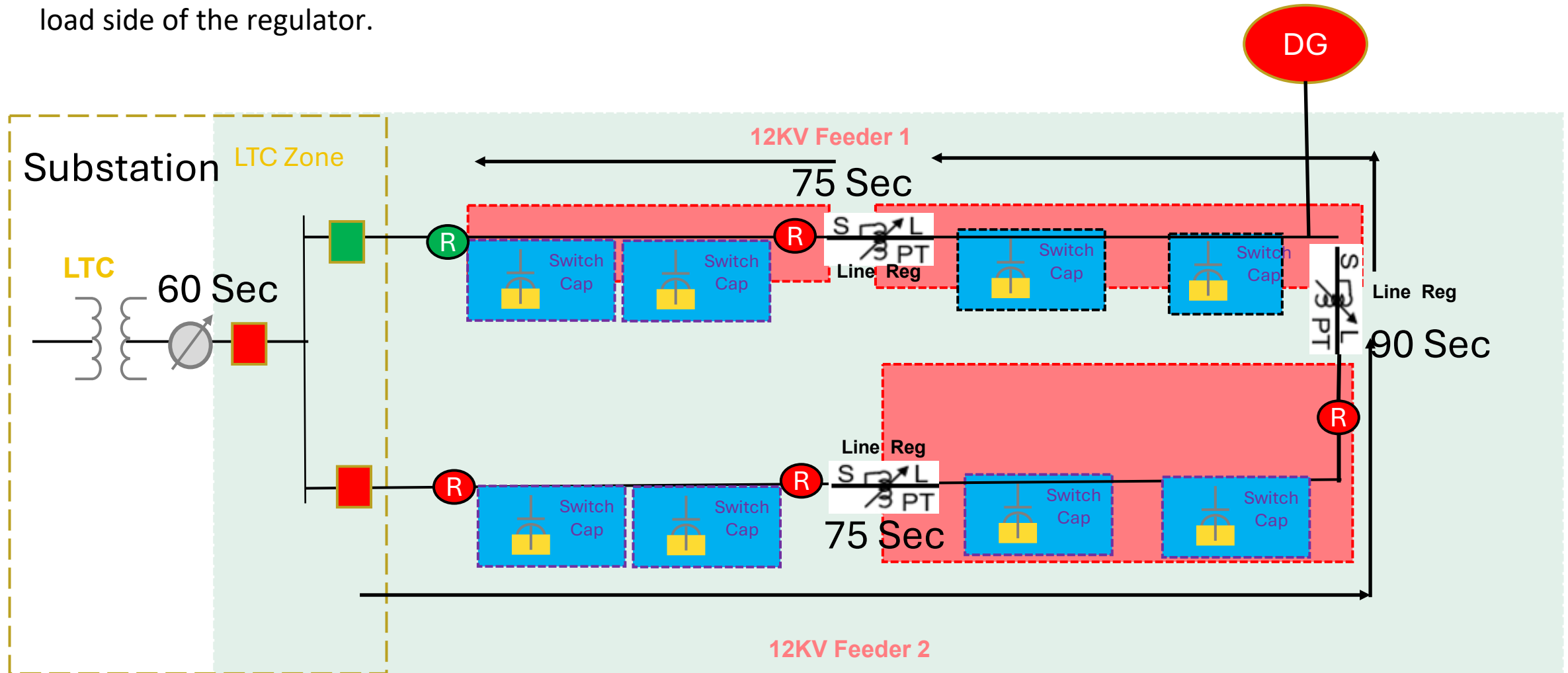
Typical Feeder with Utility Solar

1. The DG starts producing enough power that it is supplying all the load on the load side of the regulator and some of the load on the source side of the regulator, making the regulator detect reverse power flow. The voltage continues to climb at the end of the line. If the voltage-controlled cap banks were closed near the end of the line, they will open. With reverse power due to only DG the regulator controller should operate in the DG or Con-Gen Mode.



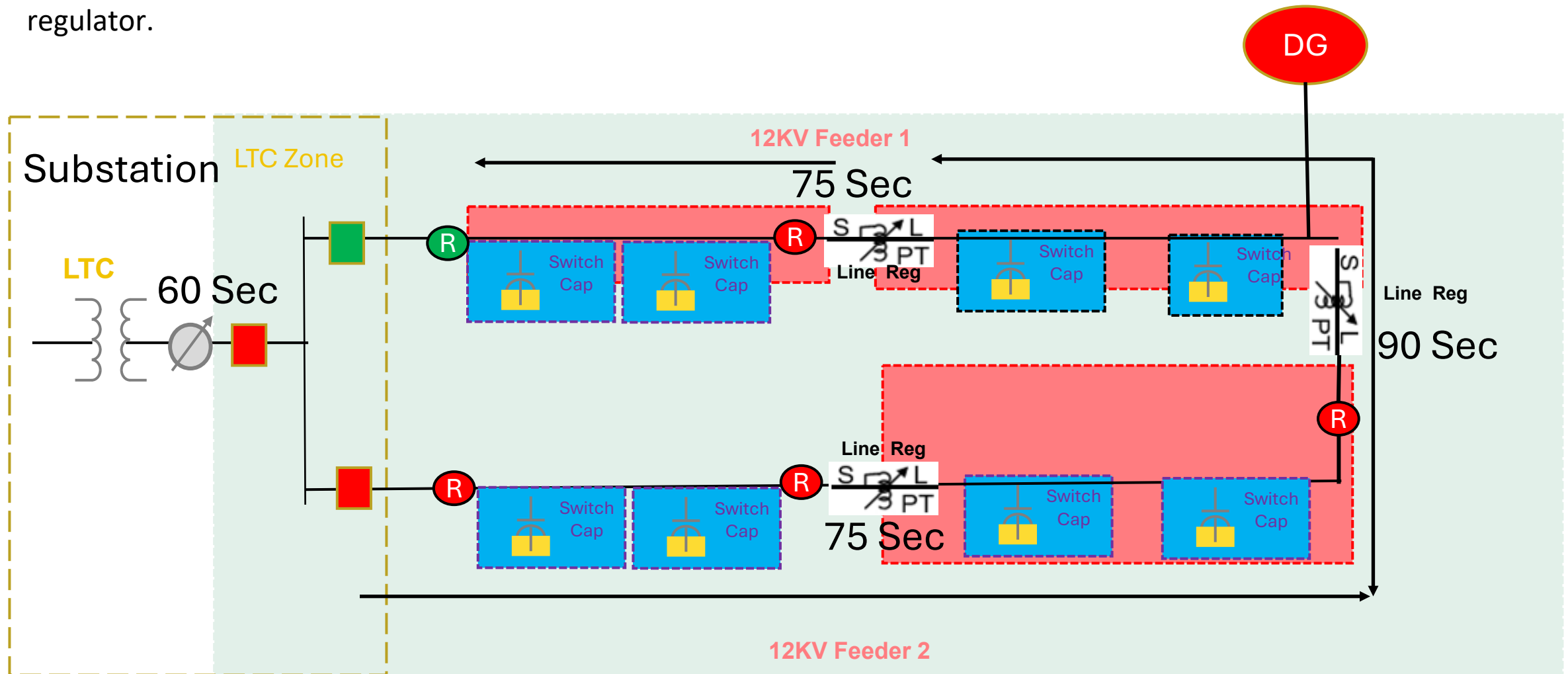
Switched Configuration Switching Reverse Power Modes

The top regulator and the NO Tie regulator are in reverse due to both the DG and the switching. In this case the regulator should operate in Regulate in reverse because the substation feed is entering into the load side of the regulator.



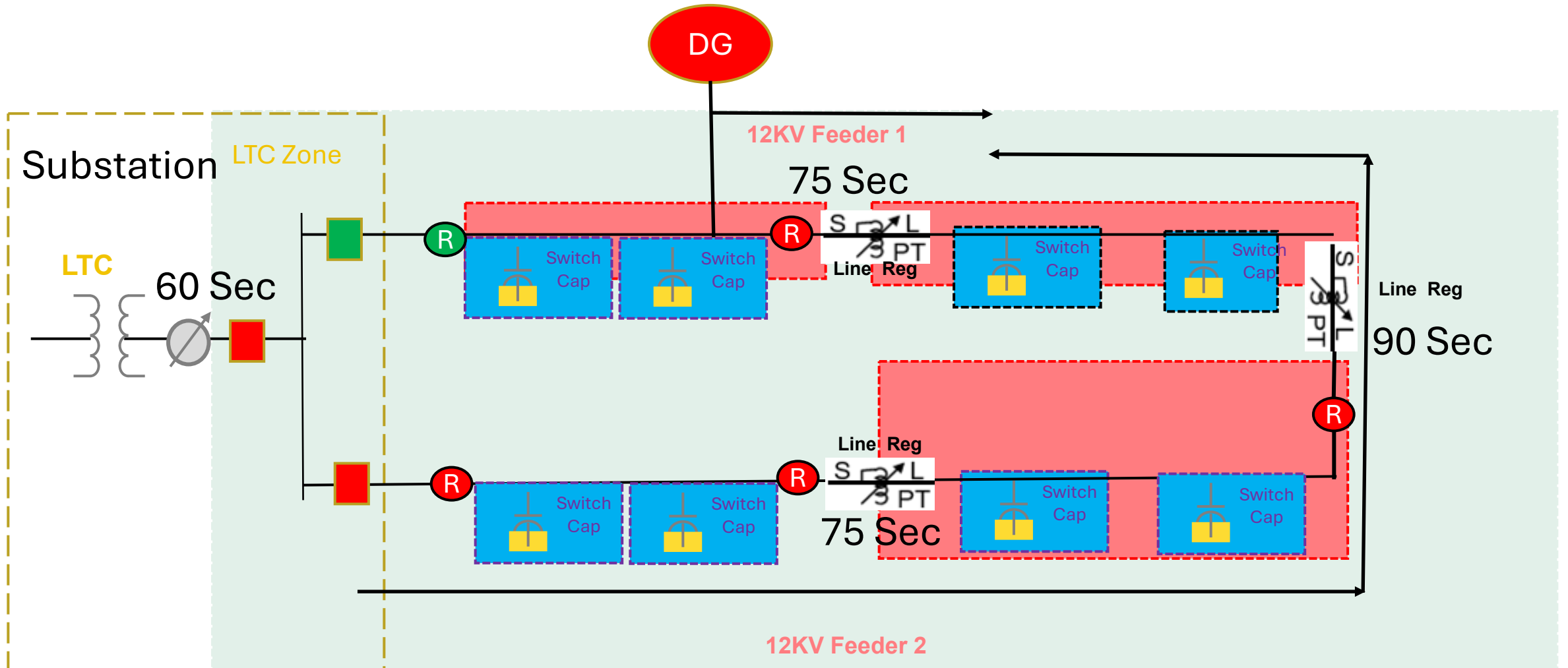
Switched Configuration – Regulators – Forward when actually in reverse

In this configuration the DG will be supply the load that has been picked up and some of the load on the other side causing the NO Line Regulator to go forward power even though its source is on the load side of the regulator.



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Abnormal Configuration Summary and DG

- DG will cause a voltage rise due to the current flowing the same impedance but in the opposite direction (negative voltage drop).
- If the circuit has a 5 volt drop across it at 600 amps and the 600 amps is flowing from the substation to the EOL the substation voltage would be 125 to get the EOL voltage at 120. If the DG pushes the 600 amps back to the substation the DG is now at 125 volts and the substation would be at 120.
- If the inverters are set to unity power the feeder must run at voltages of 119-122 to give the DG headroom to export power.
- This is a positive driver for flattening the circuit and CVR.

Abnormal Configuration Summary and DG

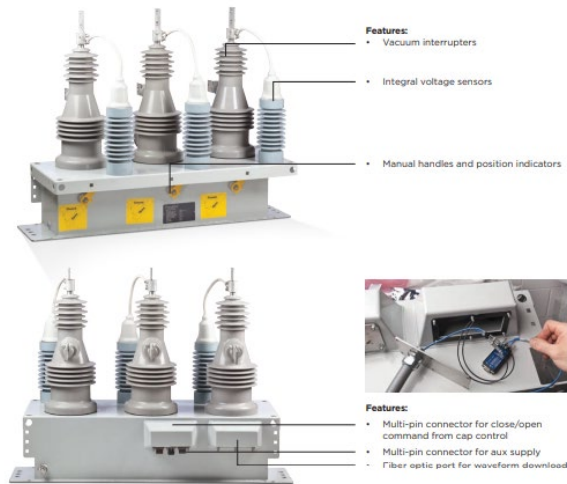
- If the DG inverters are setup in either Volt/Var or fixed pF mode they will consume Vars to lower the voltage.
- Voltage controlled cap banks will be off making the feeder lacking Vars. The Vars will come from the substation bus and therefore cause a voltage drop on the bus and cause the LTC to raise the voltage.
- Capacitor banks should be installed between the substation bus and DG but as close to the substation bus as possible and they should operate in Var Mode.
- Regulators should be set for reverse power as auto-determination in all cases.

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Hubbell Zero Close Vacuum Capacitor Switch

- DG has a variable output due to cloud coverage and this will cause the voltage to vary.
- Traditional capacitor banks can't be used to regulate this voltage variable due to their 5 minute reclose delay.
- The zero crossing switch on the capacitor banks will allow for faster operation of the cap banks and should be required on circuits with DG.



SmartClose Specifications	15kV	25kV
Rated Maximum Voltage, Phase to Phase, for Ungrounded Banks, kV, RMS	15.5	27.6
Impulse Withstand Voltage, kV, B.I.L.	110	125
Terminal-to-Ground Creep Distance, inches(mm)	18(457)	18(457)
Terminal-to-Terminal Creep Distance, inches(mm)	19(482)	19(482)
Low Frequency Insulation Level Withstand		
1 Minute Dry, kV	60	70
1 Minute Wet, kV	50	60
Continuous Current, Amps	200/400	200/400
Capacitive Switching Current, Amps	200/400	200/400
Fault Making Current Rating, Amps, Peak Assymetrical	32500	32500
Short Time Current Rating, 1 second, Amps, RMS	12500	12500
High Frequency Transient Making Current, Amps, Peak, at 6kHz	16000	16000
Operating Voltage, VAC 50/60Hz, +/-15%	120	120
Operating Current Rating, Amps	8	8
Close Command Input Voltage pulse (>90mS), AC or DC	40 to 150	40 to 150
Open Command Input Voltage pulse (>90mS), AC or DC	40 to 150	40 to 150
Environmental Operating Temperature, °C, Standard	-30 to +65	-30 to +65
Environmental Operating Temperature, °C, Optional	-50 to +65	-50 to +65
Maintenance Free Operations	30000	30000
Oil Free, Solid Dielectric	Yes	Yes
Restrike Performance, 0 restrikes	C2	C2
ANSI Test Standard	C37.66-2005	C37.66-2005
Weight, Lbs., (kg)	195(88)	195(88)

Hubbell Line Post Sensors

- When changing the capacitor controller closest to the sub from voltage to VAR control the addition of a LPS will be required

RATINGS AND SPECIFICATIONS									
Product	Current Sensor			Voltage Sensor			Current and Voltage Sensor		
Measurement Output	600A:10V			10000:1			C - 600A:10V		
	1000A:10V			1400:1	2200:1	3300:1	C - 1000A:10V		
							V - 1400:1	V - 2200:1	V - 3300:1
Nominal Rating (kV)	15	27	35	15	27	35	15	27	35
Rated Line to Ground Voltage (kV)	8.66	15.59	20.21	8.66	15.59	20.21	8.66	15.59	20.21
Positive Impulse Rating or BIL (kV)	110	150	170	110	150	170	110	150	170
Withstand Rating (kV)									
60Hz Dry Withstand	34	40	50	34	40	50	34	40	50
60Hz Wet Withstand	34	40	50	34	40	50	34	40	50
Leakage Distance (Inches)	23.2	35.4	35.4	23.2	35.4	35.4	23.2	35.4	35.4
Dry Arcing Distance (Inches)	9.7	13.2	13.2	9.7	13.2	13.2	9.7	13.2	13.2
Overall Height (Inches)	12.3	15.8	15.8	12.3	15.8	15.8	12.3	15.8	15.8
Partial Discharge Test Voltages (kV)	11	20	27.4	11	20	27.4	11	20	27.4
Maximum Pico Coulomb	10 pC or less at PD Test Voltage								
Weight (lbs)	17	21	21	17	21	21	17	21	21
Ultimate Cantilever Strength* (lbs)	2800	2800	2800	2800	2800	2800	2800	2800	2800
Temperature Range	65° C to -45° C								
Current Signal Output (CMI and CVMI)									
Ratio	600A:10V (or) 1000A:10V								
Output Burden/Load	1 Meg Ohm or Greater								
Accuracy	± 1%								
Phase Shift	0° nominal, ± 1.5°								
Sensors are calibrated at 300A for best accuracy across load current range of 0-600A.									
Voltage Signal Output (VMI and CVMI)									
Ratio	10000:1 / 1400:1 / 2200:1 / 3300:1								
Output Burden/Load	1 Meg Ohm or Greater								
Accuracy	± 1%								
Phase Shift	0° nominal, ± 1°								



Independent Phase Operated Caps for Residential PV

Per Phase Operation of Cap Banks

1. Residential PV is single-phase and there are more residential PVs on one phase than the others it can cause voltage imbalances.
2. Having a voltage-controlled capacitor bank with independent phase operation should be required if there are feeder or line regulators (LTC is gang operated).

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