34.5/115 kV Solar Power Plant & Substation Senior Design Project

Senior Design Team 18 - May 2024

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Agenda

- Safety Moment
- Calculation Documents
- Equipment/Pricing Updates
- AutoCAD Update
- ETAP
- Feedback

Safety Moment - Working with Heat & Flames

NFPA 51B: Standard for Fire Prevention During Welding, Cutting, and Other Work,

Image link

Hot work, such as welding, cutting, and heating, involves various hazards related to fire, burn injuries, health risks, electrocution, and mechanical and compressed gas hazards.

Hazards:

1. **Fire and Burn Injuries**: Hot work generates intense heat, sparks, and flames, risk to fires and burn injuries to workers and the surrounding environment.
1. **Health Hazards:** Exposure to welding fumes, gases, and airborne contaminants can cause respiratory problems, eye irritation, and other health issues.
2. **Electrocution and Electric Fire:** Inadequate electrical safety measures during hot work can result in electric shock, fires and endangering workers' lives and property.
3. **Mechanical Hazards:** Working with heavy machinery, tools, and equipment can lead to injuries such as cuts, abrasions, and crushing incidents if proper safety protocols are not followed.
4. **Compressed Gas Hazards:** Improper handling and storage of compressed gas cylinder can result in explosions, gas leaks, and other hazards, leading to severe injuries and property damage.

Safety Precautions/Control Measures:

- Hot Work Permit
- Zero LEL Level
- Isolation and Gas Testing
- Welding Booth and Fire Blankets
- Protection for Elevated Work Areas
- Compressed Gas Cylinder Safety
- Good Housekeeping
- Fire Extinguishing Equipment
- Fire Watcher
- Inspection of Equipment
- Proper Equipment Placement
- Generator Safety
- Cable and Equipment Placement
- Personal Protective Equipment (PPE):

Reference: https://www.safetynotes.net/hot-work-safety/

Calculations

AC Load Calculation :

Total worst case load:
37.267 kW or
40.994 (10% worst case scenario added)

Assumptions

1. 180VA load per Outlet assumed as worst case
2. The worst case scenario will be as follows:
   a) Time of day: Day (no lights on).
   b) Temperature: 90 deg F (all Transformer fans on).
   c) Battery: Deep discharge (charger on full).
3. Worst case tripping conditions shall be as follows:
   a) XXXX fault
      - (1) XXX Breaker will trip
      - (1) XXX Breakerwill trip

- Ratings estimated.

Calculations

The continuous 120/240VAC single phase loads are as follows:

AC Panel - Control Building

	Quantity	Load/Unit(W)	Amps (ea)	Voltage(V)	Total(W)	Amps Total
Breaker Recepticle and Lights	1	210	1.75	120	210	1.75
Transformer Fans	1	24,000	100.00	240	24,000	100.00
Transformer Sump Pump	1	2,000	8.33	240	2,000	8.33
Control House Lighting	20	36	0.30	120	720	6.00
Yard Lights	1	55	0.46	120	55	0.46
HVAC System	1	10,000	41.67	240	10,000	41.67
Fire Detection Equipment	1	150	1.25	120	150	1.25
Exhaust Fan	1	132	1.10	120	132	1.10
			#DIV/0!		0	#DIV/0!
			#DIV/0!		0	#DIV/0!
			#DIV/0!		0	#DIV/0!
			#DIV/0!		0	#DIV/0!
			#DIV/0!		0	#DIV/0!
Worst Case Tripping:						
			#DIV/0!		0	#DIV/0!
			#DIV/0!		0	#DIV/0!
Total Worse Case AC Panel Load					37,267	#DIV/0!

Total Worst Case Load (+10 %)	**40,994**	**#DIV/0!**

Sizing Recommendations:
Station Service - XXkVA
MTS, Safety Switch - XXA

recommend XXXA Station Service Equipment

1. Breaker tripping load is temporary
2. 10% worst case scenario is added to the final value

https://docs.google.com/spreadsheets/d/1hwF8cv3VBiy1_Yih5wwwBzs9P8UB_BBc/edit?usp=sharing&ouid=101132689819119398819&rtpof=true&s

Calculations

DC Load & Battery Sizing :

1. Fill out the DC Load Profile below. Read the assumptions and notes below the table.
2. Determine and record the current load amounts for 3 periods:
   a. Period 1: T=0min Fault occurs, relays detect. Breakers Trip due to relay operation.
   b. Period 2: T=1min Breakers are open, everything else is simply running.
   c. Period 3: T=240min Fault is cleared, relays operate to close Breakers
3. Create an account for the Enersys Battery Sizing Program https://bsp.enersys.com/bsp/index.do and enter your parameters to obtain a full battery system and PDF of the sizing report. This should give you a breakdown of the Amp-hours for the time periods determined.

Some notes on the table above and how to use it:

- Continuous load will be the above parameters NOT INCLUDING the trip coils from the breakers.
  - o Keep in mind, there will be more than one of each type of relay, use your zones of protection to keep in mind how many of each there are.
    - 34.5kV Feeder position (array) –Primary SEL-411L, Backup SEL-451
    - Transformer Position – Primary SEL-487E, Backup SEL-451
    - 115kV Line Position – Primary SEL-411L, Backup SEL-311L
- There will be 3 periods of operation:
  - o Period 1: T=0min Fault occurs, relays detect. Breakers Trip due to relay operation.
  - o Period 2: T=1min Breakers are open, everything else is simply running.
  - o Period 3: T=240min Fault is cleared, relays operate to activate the Breaker close-coils, bringing the Breakers back into the closed position for normal operation.
- Last item listed are LED Lamps. These will be placed around the substation yard to illuminate important equipment and cabinets. Assume we have 8 of these.
- Assume a 60 Cell system
- Use device cut-sheets to find SEL parameters (you will need to create an account, should be quick to create!) for the relay current-draw.

DC Load & Battery Sizing (IEEE 485)

Extra Reference: https://ewh.ieee.org/r3/atlanta/ias/2014-2015_Presentations/2015-04-20_EEE%20IAS%20Stationary%20Battery%20Sizing.pdf

DC Load Profile

Components	Load Current (A)	Nominal Voltage (V) DC	Inception and Active Shutout Time (Min.)	Power Requirement (remember to account for # of relays required)	Number of Components
34.5kV Breaker:	Tripping Current: 3.3A Closing Current: 2.6A	70 – 140 90 - 140	0 -1	231 - 343W 234 - 364W	
115kV Breaker:	Tripping Current: 3.3A Closing Current: 2.6A	70 – 140 90 - 140	239- 240	462 - 924W 324 – 504W	
SEL-411L		125	1 - 240		
SEL-311L		125	1 - 240		
SEL-4207		125	1 - 240		
SEL-487E		125	1 - 240		
SEL-451		125	1 - 240		
Battery Monitoring Equipment	0.024A	50 -180	1 - 240	6VA	
DC Ammeter	0.048A	125	1 - 240	3VA	
DC Voltmeter	0.048A	120	1 - 240	3VA	
SACO Annunciator (L8)		125	1 - 240		
Edwards Bell	0.012A	125	1 - 240	1.5VA	
Power Line Indicating Lamps (LEDs)	0.017A	125	1 - 240		8

60 cell system	Continuous Load	Discontinuous Load Current

	T = 0	T = 1 min	T = 240 min

https://docs.google.com/spreadsheets/d/1xRuwZ2yvrR49pMpPJpyQim3Ds8Mtx1fYL_kV4MVxrck/edit?usp=sharing

Calculations

Grounding calculation:

Requirements:

1. Find the uniform soil resistivity (ρ_a) in ohm-m using the given soil resistivity measurements.
2. Find the minimum conductor size (in kcmil) for a copper, soft-drawn grounding conductor. (Although the minimum value may be significantly smaller, 4/0 AWG is typically the smallest size conductor used in a substation grounding grid)
3. Find the tolerable Step (E_{STEP}) and Touch (E_{TOUCH}) voltages with a surface layer derating factor $C_s = 0.8$. (Note that equations are 31-33 are labeled incorrectly as step equations. They are touch equations)
4. Design a square grid for the given substation area and find the maximum step (E_s) and maximum mesh/touch (E_m) voltages. Refine the ground grid design as needed so that the maximum step/touch voltages are less than the tolerable step/touch voltages that were found in problem 3. If needed, use ground rods with a length of 20'.
5. Provide a drawing of the ground grid in the proposed substation area showing grid spacing distances. Industry standard typically has the ground grid extend 3 feet outside the fence line.
6. Provide a short report that includes references, any assumptions made, and final results (please include equations and calculations, even if hand-written).

Given parameters for grounding

Parameters	Value	Unit	Symbols
Maximum grid current	32	kA	Ig
Fault duration for conductor sizing	1	s	tc
Shock duration	0.5	s	ts
Surface layer thickness	0.15	m	hs
Surface layer resistivity	3000	ohm-m	ps
Body weight	50	kg	w
Ambient temperature	40	C	T
Grounding conductor depth	0.15	m	h
Grid reference depth	1	m	h0
Dimension of fence (x)	160,48.768	ft, m	
Dimension of fence (y)	100, 30.48	ft,m	

Parameters to calculate/find

Parameters	Value	Unit	Symbols
Number of parallel conductors			n
Spacing between n parallel conductors		m	D
grid conductor diameter		m	d
Total length of conductor in the horizontal grid		m	Lc
Perimeter length of grid		m	Lp
Area of the grid		m^2	A
Max length in the x direction		m	Lx
Max length in the y direction		m	Ly
Max distance between any two points on the grid		m	Dm
Total length of rod		m	LR
Length of each rod		m	Lr

$$n = n_a \times n_b \times n_c \times n_d$$

$$n_a = \frac{2 \times L_C}{L_p}$$

$$n_b = \sqrt{\frac{L_p}{4 \times \sqrt{A}}}$$

$$n_c = \left[\frac{L_x \times L_y}{A}\right]^{\frac{0.7 \times A}{L_x \times L_y}}$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}}$$

1 Calculation for the uniform soil resistivity (pa) in ohm-m

Probe Spacing (ft)	Apparent Resistivity (ohm-m)
1	120
2	85
3	65
6	48
10	32
20	24
30	20

2 Calculation for Minimum Conductor Sizing

Description	Material conductivity (%)	α_r factor at 20 °C (1/°C)	K_o at 0 °C (0 °C)	Fusing[a] temperature T_m (°C)	ρ_r 20 °C (μΩ·cm)	TCAP thermal capacity [J/(cm³·°C)]
Copper, annealed soft-drawn	100.0	0.003 93	234	1083	1.72	3.42

3 Calculation for Tolerable Step Voltage

$$E_{step50} = (1000 + 6C_s \cdot \rho_s)\frac{0.116}{\sqrt{t_s}}$$

E(step50)	

4 Calculation for Tolerable Touch Voltage

$$E_{touch50} = (1000 + 1.5C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}}$$

E(touch50)	

5 Calculation for Maximum Step Voltage

$$K_s = \frac{1}{\pi}\left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D}(1 - 0.5^{n-2})\right]$$

Ks

$$K_i = 0.644 + 0.148 \cdot n$$

Ki

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R$$

Ls

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_S}$$

Es

6 Calculation for Maximum Touch Voltage

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}}$$

Kii

$$K_h = \sqrt{1 + \frac{h}{h_o}} \quad h_o = 1\text{m (grid reference depth)}$$

Kh

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d}\right] + \frac{K_{ii}}{K_h} \cdot \ln\left[\frac{8}{\pi(2 \cdot n - 1)}\right]$$

Km

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right]L_R$$

Lm

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M}$$

Em

Task : Find outer dimension of substation fence

160' by 100' (ft) or
48.768 by 30.48 (m)

https://docs.google.com/spreadsheets/d/1xRuwZ2yvrR49pMpPJpyQim3Ds8Mtx1fYL_kV4MVxrck/edit?usp=sharing

Calculations

Bus calculation:

1. Ampacity
2. Bus Force
3. Maximum Allowable Span

Bus calculation (IEEE 80) - Ampacity

Variable	Description	Value	Unit
ΔT	Temperature difference between ambient and conductor surface	50	°C
T2, Tc	Conductor Temperature	90	°C
Ɛ	Emissivity	0.2 for new aluminum	
		0.5 for weathered	
		aluminum	
Ta	Ambient Temperature	40	°C
Ɛ'	Solar absorption	0.5	
E	Modulus of elasticity for aluminum	68.9x109	N/m2
FG	Gravitational Force	33.7	N/m
σ (allowable)	Allowable stress of material accounting for welds	120	MPa
wc	Specific weight of aluminum	26500	N/m3
wi	Ice weight	8820	N/m3
ri	Equivalent uniform radial ice thickness	0.00635	m
C	Constant, for metric units	0.613	
V	Extreme wind velocity	40	m/s
		144	km/h
Cf	Force coefficient for rigid tubular bus	1	
Gf	Gust response factor	0.85	
I	Importance factor	1.15	
ISC	Short-circuit current	15	kA
Γ	Constant based on type of fault and conductor location	0.866	
Kf	Mounting structure flexibility factor	1	
Df	Half cycle decrement factor	0.927	
η	Allowable deflection as a fraction of span length	0.0067 (1/150)	
C′	Conductivity, % IACS. For 6101-T6 alloy per Table 2	55	

1	Rigid bus calculation

Parameters	Value	Unit
DC resistance		
cross-sectional area		
surface area by unit length		
Forced convection heat loss		
radiation loss from a surface		
effective angle of incidence of sun (theta)		
effective angle of incidence of sun (angle		
heat gained from incident solar radiation		
Allowable current (I)		A

2	Flexible bus (conductor) calculation

Parameters	Value	Unit
DC resistance		
surface area by unit length		
Forced convection heat loss		
radiation loss from a surface		
heat gained from incident solar radiation		
Allowable current (I)		A

Task :

https://docs.google.com/spreadsheets/d/1B0NZYBSkD5nU1I6lLadosi6QVMOQBY21F-alNrFIGwY/edit?usp=sharing

Alternative Relays

- GE Multilin T35: Transformer protection relay specifically designed for ring bus setups, offers differential current and phase overcurrent protection
  https://www.gegridsolutions.com/multilin/catalog/t35.htm
- ABB REU615: Busbar under/overvoltage protection, frequency monitoring, and optional arc flash protection
  https://new.abb.com/medium-voltage/digital-substations/protection-relays/voltage-protection-and-control/voltage-protection-and-control-reu615-iec
- ABB RET630: Transformer differential, thermal overload, voltage, and hotspot protection
  https://new.abb.com/medium-voltage/digital-substations/protection-relays/transformer-protection-and-control/transformer-protection-and-control-ret630-iec
- Schneider Electric PowerLogic P3U: Universal protection relay with overcurrent detection, breaker failure detection, and reclosing capabilities
  https://www.se.com/us/en/product/REL52052/universal-protection-relay-powerlogic-p3u-3ct-1io-ringlug-1vt-8di-8do-48230v-di110v-2rj45-ansi/?range=64884-powerlogic-p3-protection-relays&parent-subcategory-id=4655&selectedNodeId=12144299041

Equipment Pricing

- 115 kV Breaker: $95,000 - $100,000

https://www.bid-on-equipment.com/electrical-and-electronic/electrical-equipment/control-panels-and-switchgear/280392~siemens-sf-hexafluoride-substation-circuit-breaker---115-kv-new-surplus.htm

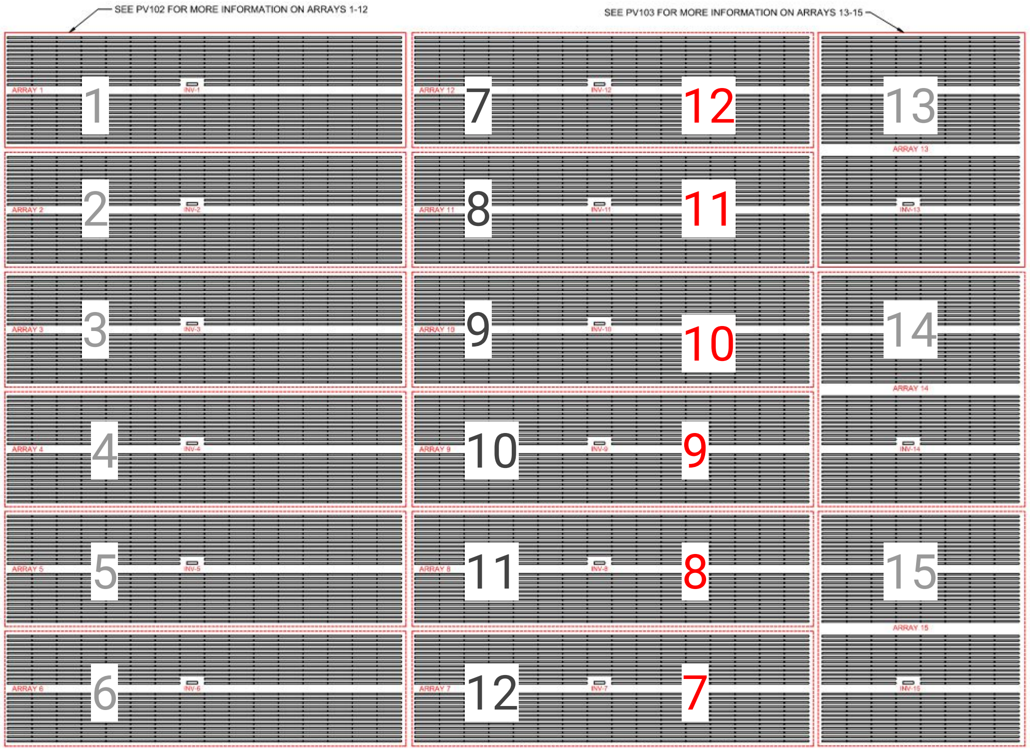
- Pricing Website

https://peguru.com/substation-cost-estimator/
chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.icc.illinois.gov/downloads/public/edocket/534802.PDF

- The Illinois Commerce Commission is a quasi-judicial tribunal that regulates public utility services in the U.S. state of Illinois
- Example costs from site
  - 100 MVA Transformer: $1,500,000
  - 138 kV Breaker: $80,000
  - 35 kV Breaker: $35,000

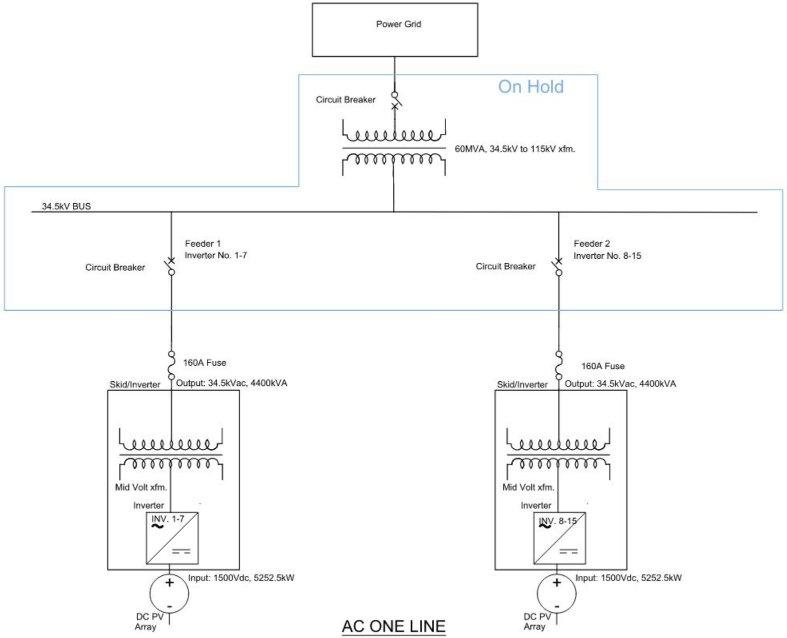
Notes:
Prices from this site seem to match suggested prices when additional 25% is applied. Website offers very extensive equipment options.

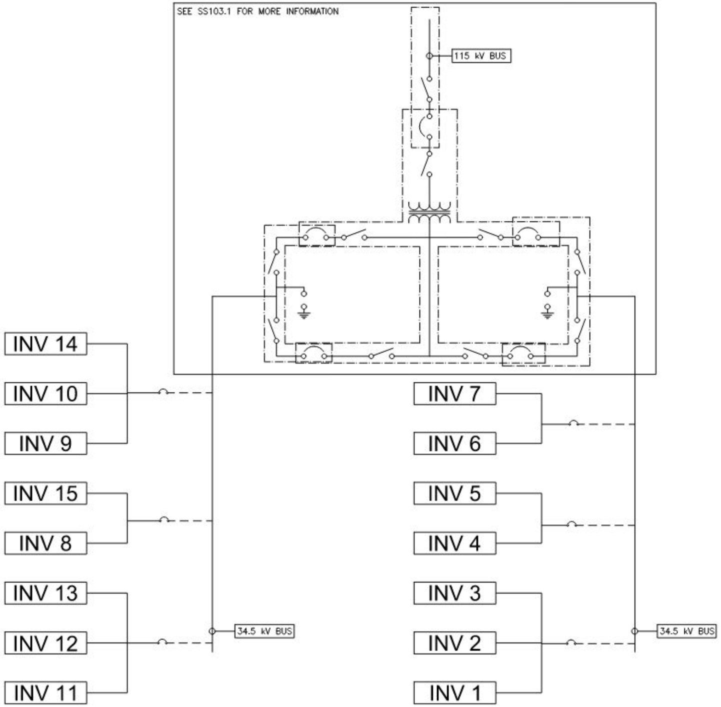
AutoCAD - Array Renumbering



SOLAR FARM KEY PLAN

AutoCAD - Array Renumbering





AutoCAD - Equipment Schedules

	Pmax (W)	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	Mod Eff (%)
PVX-Y-Z.Z	550	41.90	13.13	50.20	13.89	21.29

Model No. ZXM7-SHDB144

	Vmax (V)	Input #	Imax in (A)	Imax out (A)
CBX-Y	1500	16	30	350

Model No. BHTZ-16/1

	INPUT (DC)			OUTPUT (AC)			
	PVmax (kWp)	DC Volt Range (V)	DC Inputs	Snom (kVA)	Smax (kVA)	Output Freq (Hz)	Inv Eff (%)
INV-X	2 x 3200	935-1500	24	4000	4400	60	98.8

Model No. PVS980-MWS-4000kVA-K

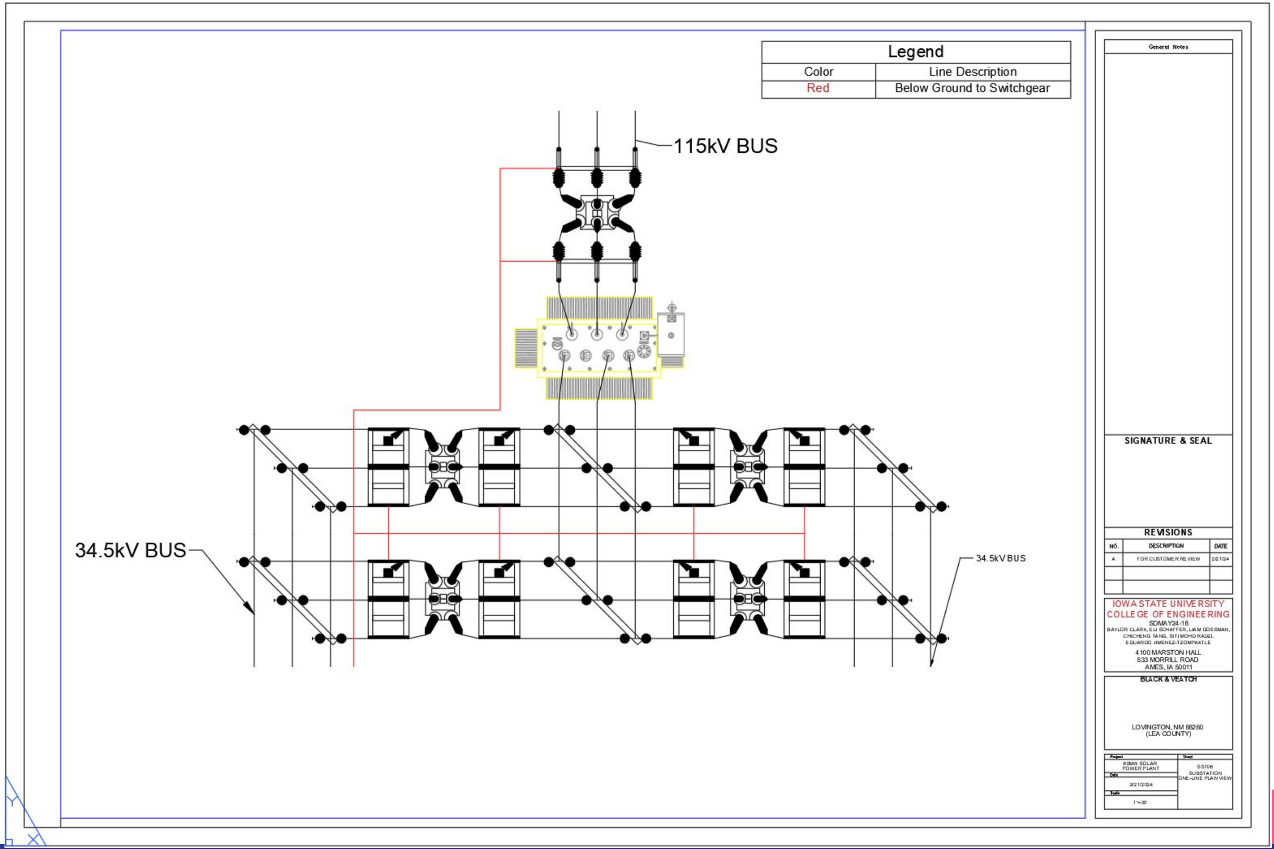
	Vmax (kV rms)	Isc (kA rms)	Curr Rating (A rms)	Model No.	
CB1-X	38	16	1600	380 VCP-W 16C	SEE SS110 FOR MORE INFO
CB2-X	126	40	3150	LW25A-126	SEE SS111 FOR MORE INFO

	Vmax (kV rms)	Isc (kA rms)	Curr Rating (A rms)	Model No.	
DS1-X	38	16	2000	VacClad W 38kV	SEE SS112 FOR MORE INFO
DS2-X	121	40	2000	657428-Z3	SEE SS113 FOR MORE INFO

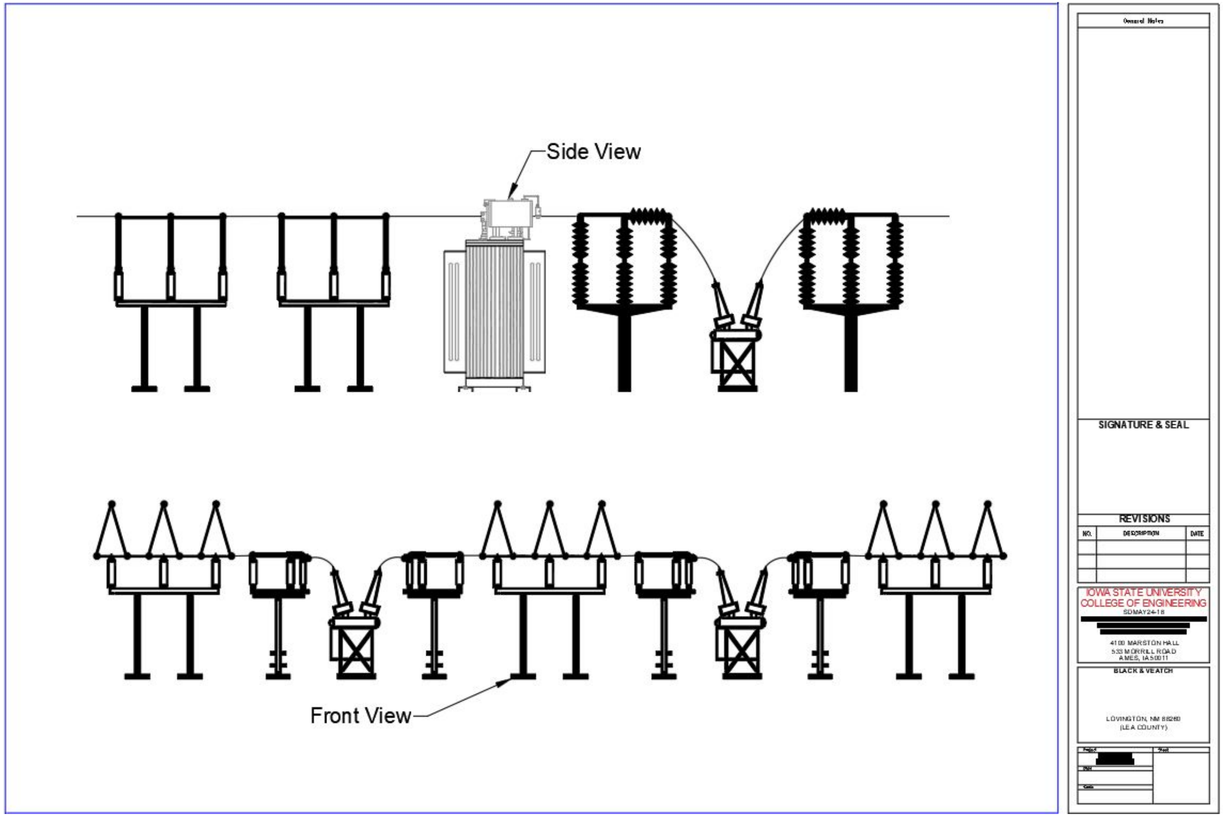
	Vnom (kV)	Vmax (kV)	Isc (kA rms)	Model No.	
LA1-X	36	217	63	USAA036A	SEE SS114 FOR MORE INFO

	LOW SIDE		HIGH SIDE				
	Vnom (kV)	Inom (kA)	Vnom (kV)	Inom (A)	Rating (MVA)	Model No.	
T1	34.5	1.5	115	451.8	90	SF-900000/115	SEE SS115 FOR MORE INFO

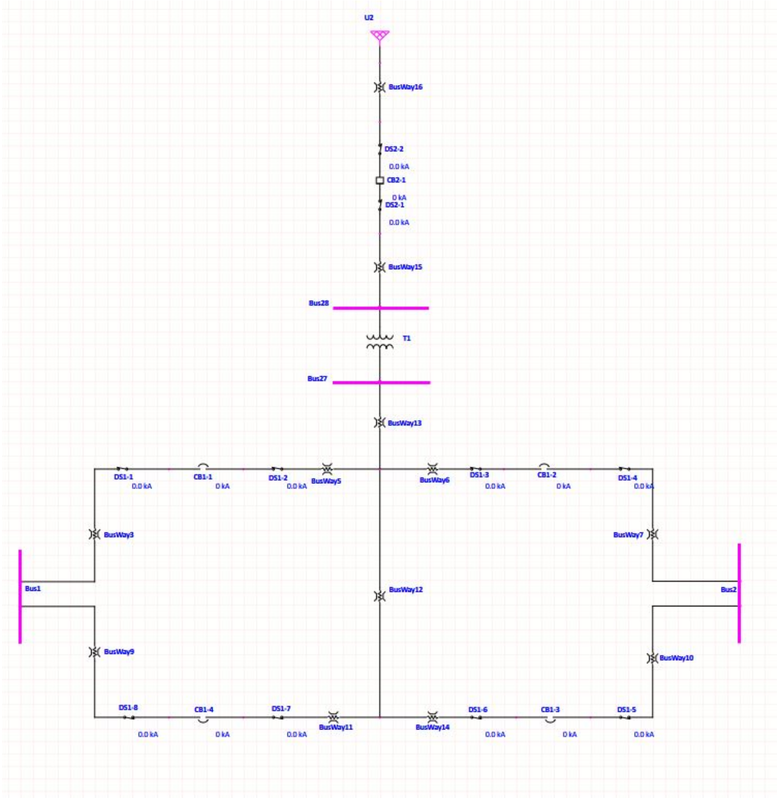
AutoCAD - One Line Plan View



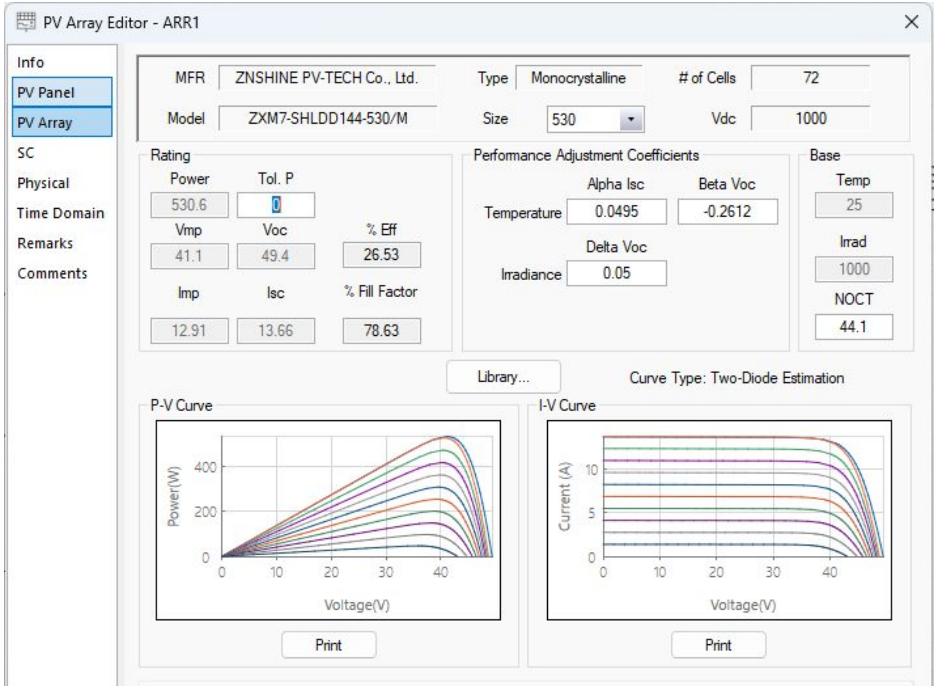
AutoCAD - SS Section View

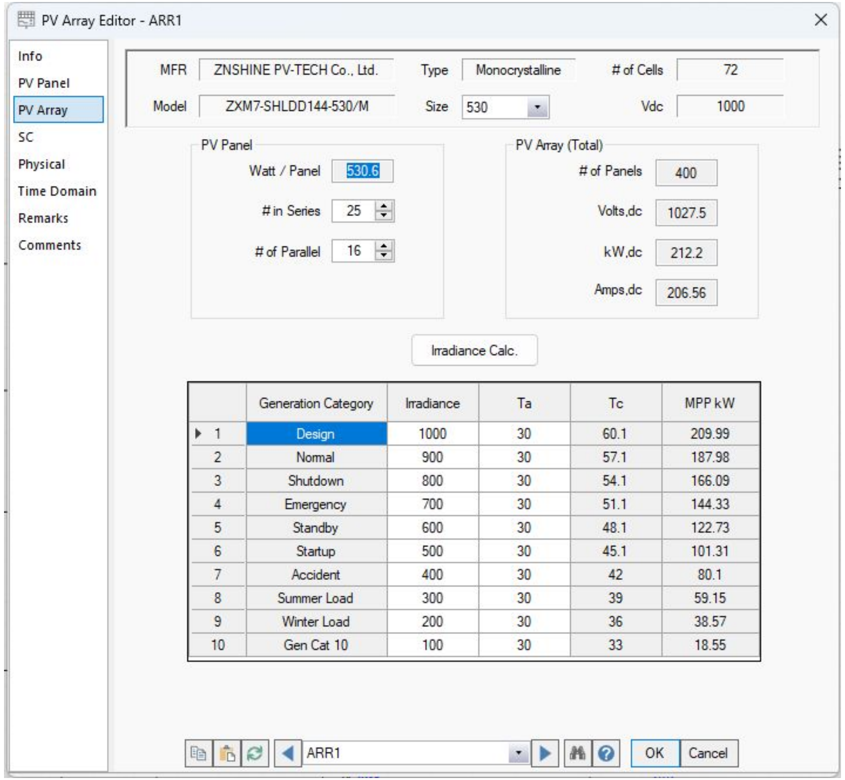


ETAP - Substation



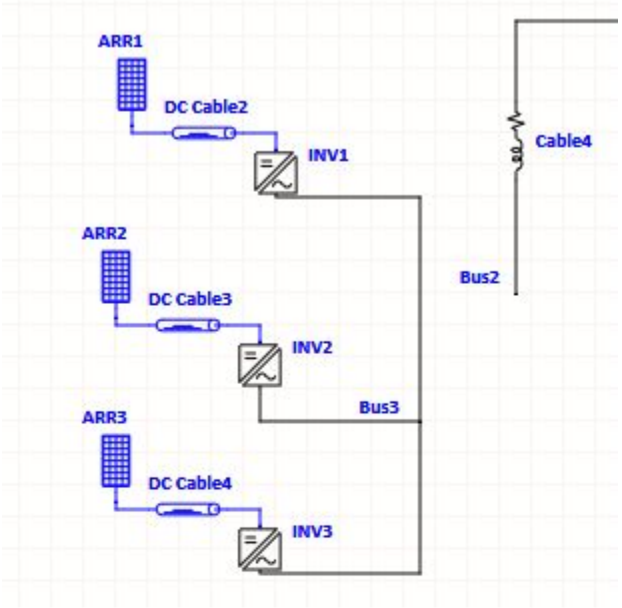
ETAP - PV Power Flow

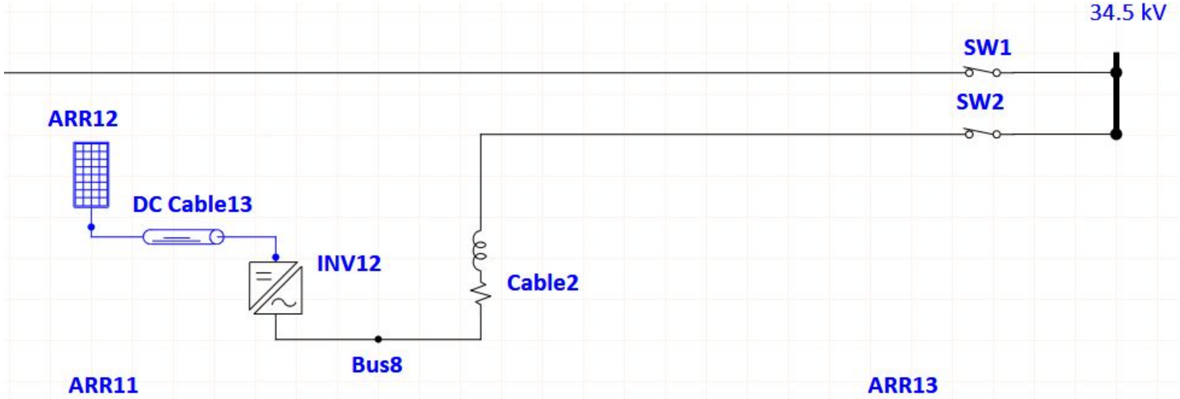




	Generation Category	Irradiance	Ta	Tc	MPP kW
1	Design	1000	30	60.1	209.99
2	Normal	900	30	57.1	187.98
3	Shutdown	800	30	54.1	166.09
4	Emergency	700	30	51.1	144.33
5	Standby	600	30	48.1	122.73
6	Startup	500	30	45.1	101.31
7	Accident	400	30	42	80.1
8	Summer Load	300	30	39	59.15
9	Winter Load	200	30	36	38.57
10	Gen Cat 10	100	30	33	18.55

ETAP - PV Power Flow





Questions

- Next steps
    -

Feedback and Updates

- Tasks: Updates
    - Bell:
    - Liam:
    - Eli:
    - Baylor:
    - Eduardo:
    - Chicheng: