115 kV / 34.5 kV Solar Power Plant / Substation

Design Document

MAY1602

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CONTENTS

1 OVERVIEW

Solar power generation is a renewable method of proving electrical power to a grid or load. The solar plant will produce power which will be directed to the grid via a substation. The plant will contain the solar arrays and inverters. The substation contain all necessary components including transformers, protection relays, monitoring equipment, and capacitor bank.

1.1 Project Scope

Due to increasing renewable energy standards set by RES, Black & Veatch is sponsoring a senior design project to design a 60 MW grid tied solar power plant with an attached 115kV/34.5 kV substation. The senior design team will design both parts of the project including the solar layout, substation layout, and associated deliverables.

1.1.1 Project Scale

Due to the large scale of the solar power plant and substation project, two Black & Veatch engineers will manage the senior design team's design and schedule.

1.1.2 Utilized Software

The software requirements for this project are AutoCAD, HelioScope, and Microsoft Office products.

1.1.3 Deliverables

The first semester deliverables will consist of the following documents:

- Solar plant array parameters.
- Solar plant layout drawings.
- Substation one-line drawings.
- Conductor sizing.
- Engineering man-hour budget.

The second semester deliverables will consist of the following documents:

- Optimized solar plant array parameters.
- Optimized solar play layout drawings.
- Substation three-line drawings.
- Engineering man-hour budget.

1.1.4 Physical Layout

Solar arrays will be the vast majority of the space requirement, the substation space requirement is minimal. The team is responsible for determining space requirements for the entire project.

1.1.5 Drawings and Documentation

The proper documentation of the design will be the responsibility of the senior design team. Detailed drawings for the solar array and substation will be required. The first semester will focus on the solar generation schematics and one-line drawings for the substation. During the second semester the team will begin detailed three-line drawings for the substation.

1.1.6 Project Schedule and Budget

First and second semester engineering schedule is laid out in figure 1. The spring 2016 schedule is a projection as of December 2015. The first semester of the design project will consist mainly of solar plant sizing, plant layout, substation layout, component sizing, circuit protection, and budget. The second semester will consist of finalization of design including but not limited to detailed three-line substation drawings, optimization, and presentation to faculty and Black & Veatch.

Figure 1 shows a budget and actual hours spent on design. Additionally, it shows the percent over or under budget of actual hours. The yellow box shows the billable hours as per budget. The actual man-hour budget is considerably above projections. But it was a learning experience.

115 kV / 34.5 kV Solar Power Plant / Substation

Start Week **Aug 31, 2015**

Break | Projected | Overrun | Billable Hours

FALL 2015

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Start Date	Aug 31	Sep 7	Sep 14	Sep 21	Sep 28	Oct 5	Oct 12	Oct 19	Oct 26	Nov 2	Nov 9	Nov 16	Nov 23	Nov 30	Dec 7	Dec 14	Tasks/Assignements
																	Meetings-client & advisors
																	Assign tasks/ begin research
																	Team roles/advisors meetings
																	Discuss project scope with client
																	Solar plant size determination
																	Project Plan V1
																	Design document V1
																	Solar array parameters
																	Solar array layout
																	Solar plant conductors
																	Substation one-line drawings
																	Substation three-line drawings
																	Project Plan V2
																	Design Document V2
																	Presentation slides and rehearsal
																	Faculty presentation
																	Finalize deliverables
																	SUM
Hours Budget	5.0	10.0	10.0	10.0	20.0	20.0	20.0	30.0	30.0	15.0	15.0	30.0	0.0	40.0	10.0	2.0	267.0
Hours Actual	4.0	10.0	8.5	16.5	25.0	16.5	44.0	37.0	24.0	16.0	18.0	31.5	0.0	59.0	29.5	1.0	340.5
% of Budget	80	100	85	165	125	83	220	123	80	107	120	105	0	148	3	1	127.5

Start Week **Jan 11, 2016**

Break | Projected | Overrun | Billable Hours

SPRING 2016

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Start Date	Jan 11	Jan 18	Jan 25	Feb 1	Feb 8	Feb 15	Feb 22	Feb 29	Mar 7	Mar 14	Mar 21	Mar 28	Apr 4	Apr 11	Apr 18	Apr 25	Tasks/Assignements
																	Meetings-client & advisors
																	Fall 2015 review
																	3-line ac drawings
																	3-line 89 drawings
																	3-line bank drawings
																	3-line bu drawing
																	3-line comm drawings
																	3-line dc drawings/ethernet
																	3-line feeder drawings
																	Design document V3
																	Optimization
																	Presentation preperation
																	BV presentation
																	IRP presentation
																	SUM
Hours Budget	8.0	8.0	8.0	8.0	8.0	10.0	10.0	8.0	15.0	0.0	10.0	20.0	20.0	10.0	20.0	2.0	165.0
Hours Actual	7.5	18.5	19.5	17.5	4.5	9.0	16.5	23.0	41.5	0.0	8.5	24.0	34.0	19.0	25.0	2.0	270.0
% of Budget	94	231	244	219	56	90	165	288	277	0	85	120	170	190	125	100	163.6

Figure 1: Project Schedule and Budget

1.2 Project Specification

Input and output specifications are provided by Black & Veatch, these specifications may change during the design process. Additionally, all designs must meet NFPA70 National Electrical Code (NEC) requirements.

1.2.1 Solar Power Plant Specifications

The specified solar array parameters and components are as follows. The team is free to utilize any additional components and to meet or exceed specifications and IEEE standards.

- Location – Iowa
- Solar Inverter – Eaton Xpert 1670 kW
- Solar Panel – Hanwha 325 kW
- Combiner Box DC Voltage – 1500 V
- Inverter Load Ratio (ILR) – about 1.30
- Combined Solar Inverter Output – 60 MW
- Fixed Rack System

1.2.2 Substation Specifications

The substation component of the project will be based on the Arcadia single line diagram (see 5.3.2) and specifications within *System Protection Requirements* provided by Black & Veatch.

- Substation collector input voltage – 34.5 kV
- Substation point of interconnect output – 115 kV

2 HIGH LEVEL SYSTEM DESIGN

This section will outline the high level system design and explain important terms. Focus is on single-line diagrams.

2.1 System Power Flow

A solar (PV) plant consisting of arrays will output power to a grid-tied substation. The output of the plant is 60 MW. Figure 2 below shows the power flow from generation to grid (left to right). The solar power plant will produce DC current which is routed through a set of series/parallel conductors to an inverter. The inverter outputs three phase AC current to a step-up transformer. The step-up transformer outputs to a collector in the substation component, in which flows to the collector arrangement, feeder arrangement and key protection component. Finally, it is fed to the grid at 115 kV.

2.1.1 Complementary Documents

Information from complementary documents will summarized and explained in this design document. For further details and data, See list of complimentary documents below.

- *Array_Parameter_Tool_13* – This file contains all calculations, parameters, conductor sizing, and production simulation.
- *Drawing_List* – List of 30 AutoCAD drawings with task, title and status of each drawing. Also provided in *Appendix.*
- AutoCAD drawings.
- *System_Protection_Requirement*

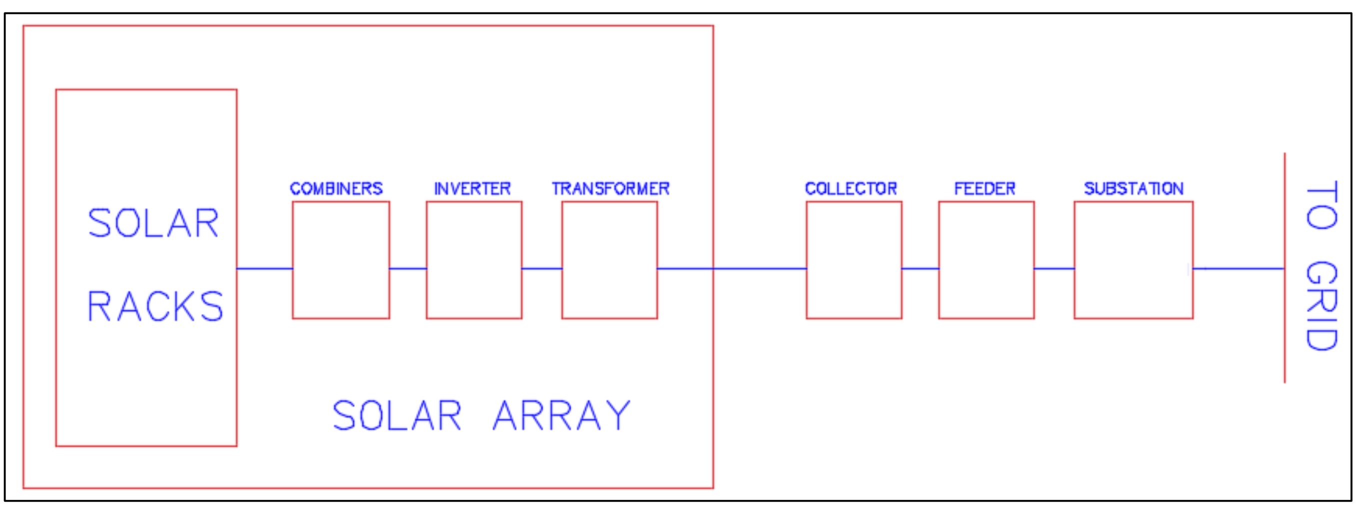


Figure 2. High Level System Block Diagram

2.2 Solar Component Design

This section will outline high level aspects of the solar component of the project.

2.2.1 Solar Land Requirements

After determining the solar modules to be used, 325 W, the calculation of space requirements for the PV plant may be accomplished as follows. 60 MW is the required plant capacity, 1.30 is the desired ILR (see *Glossary of Common Terms*) used to scale land requirement. Thus, we determined the amount of space by the following calculation:

$$Number\ of\ Panels\ Needed = \frac{60\ MW}{325\ W}(1.30) = 240000\ panels$$
$$Panel\ Area = 21.45\ ft^2$$
$$Total\ Area\ of\ Panels = 240000 * (21.45\ ft^2) = 5147990\ ft^2$$

Therefore,

$$Total\ Area\ Needed = 5147990\ ft^2 = 0.185\ mi^2 = 120\ acres$$

To split the solar panels into arrays, we divided the required output by the inverter power rating.

$$Number\ of\ Arrays = \frac{60\ MW}{1670\ kW} = 36\ arrays$$

Including the row spacing, inverter skid, and access road; the total area becomes about 240 acres for the entire solar plant.

2.2.2 Important Terms and Concepts

The following is a list of important terms and concepts referenced throughout the document.

2.2.2.1 Inverter Load Ratio

The most important factor in solar power generation design is the inverter load ratio (ILR). The ILR is the ratio of DC solar capacity and inverter AC output. Since panel production conditions and actual conditions vary significantly at any given time and day, the DC power input design should about 130% of the AC output rating. This corresponds to an ILR of about 1.30. For majority of the time, the inverter input will not output above rated AC capacity, in the times that it does, the inverters will clip output and dissipate the excess power as heat. Thus the ILR is a metric of inverter utilization.

2.2.2.2 Irradiance Correction Factor

A second safety factor called the irradiance correction factor (Isc – irradiance correction) was utilized as a failsafe for current spikes a string may experience in times of exceptionally high solar radiation.

This factor is valued at 1.25. NEC690.8(B) requires a secondary correction factor before all others. All conductors must be designed with this calculated current scalar applied.

2.2.2.3 Inverter

The inverter converts solar DC output to 3-phase output to the collector. This inverter is supplied with a matching step up transformer.

2.2.2.4 Continuous Current Multiplier

A safety multiplier, NEC690.8(A) requires overcurrent device ratings shall not be less than 125% of the maximum currents calculated. All conductors must be rated for continuous current along with the irradiance correction factor.

2.2.3 Array Layout

The arrays will be laid out in a single block containing all panels, racks, inverters and step-up transformer. There will be a total of 36 arrays in the plant. Each array measures 551.04 x 508.69 ft. See figure 3. The row spacing is 12.0 ft, the inverter access road is 16.0 ft wide.

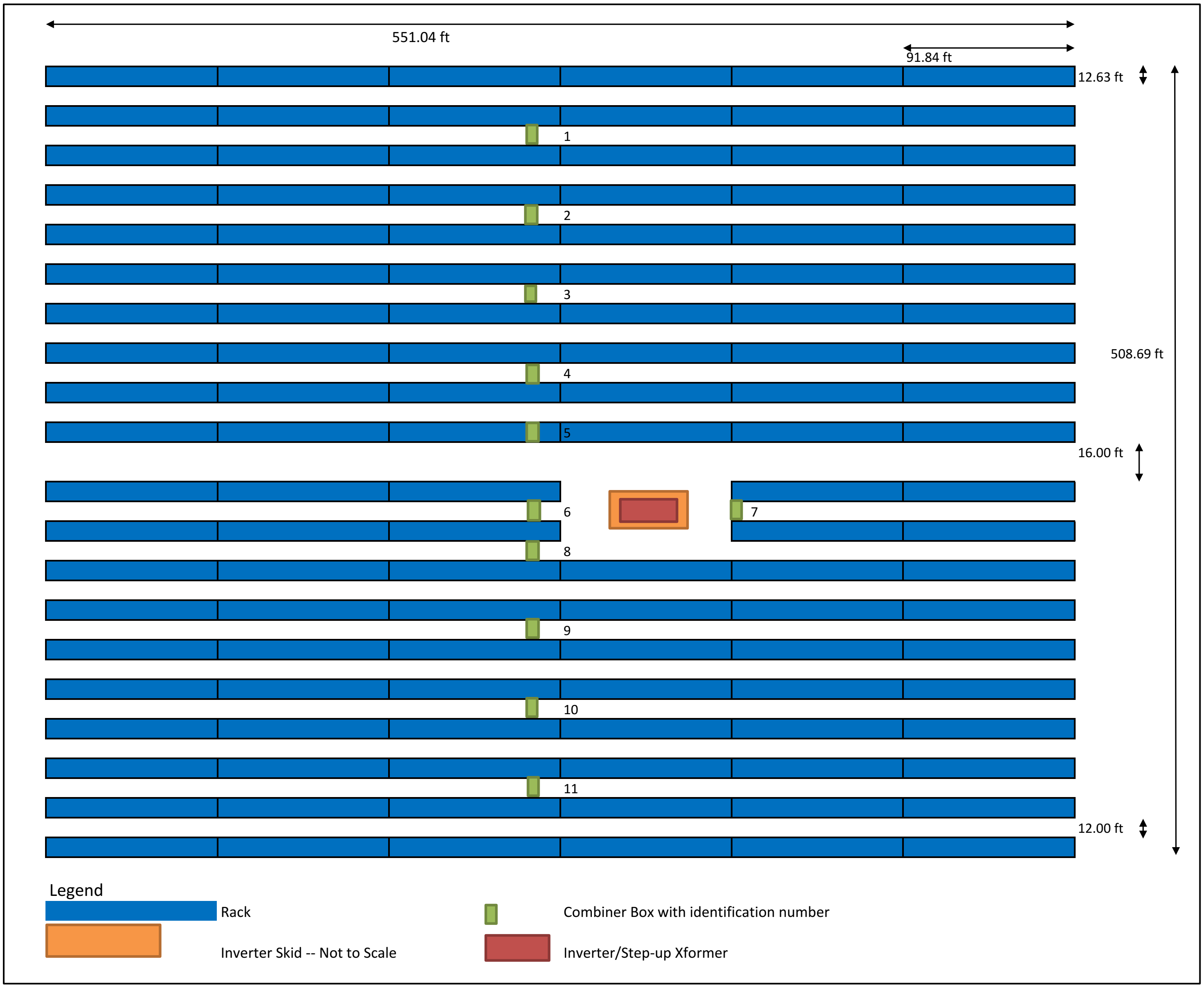


Figure 3. Single Array Layout

2.3 Substation Component Design

The purpose of the substation is to collect all solar array power and feed into the grid after stepping up voltage to distribution level. This substation is based on an Arcadia design (see 5.3.2), modified for the project. Power flow is bottom to top, 34.5 kV bus to 115 kV bus. It will consist of the following major drawings (one-line drawings).

- Collector – Input from solar arrays' transformer.
- Feeder – Output from collector, input to 34.5 kV bus.
- Key Protection – Circuit breakers, protection relays, capacitor bank, and step-up transformer. Outputs to grid at 115 kV.

The power flow block diagram in figure 4 shows the input current flow from array skids. Array skids contain the inverter and step-up transformer. Power flow is bottom to top.

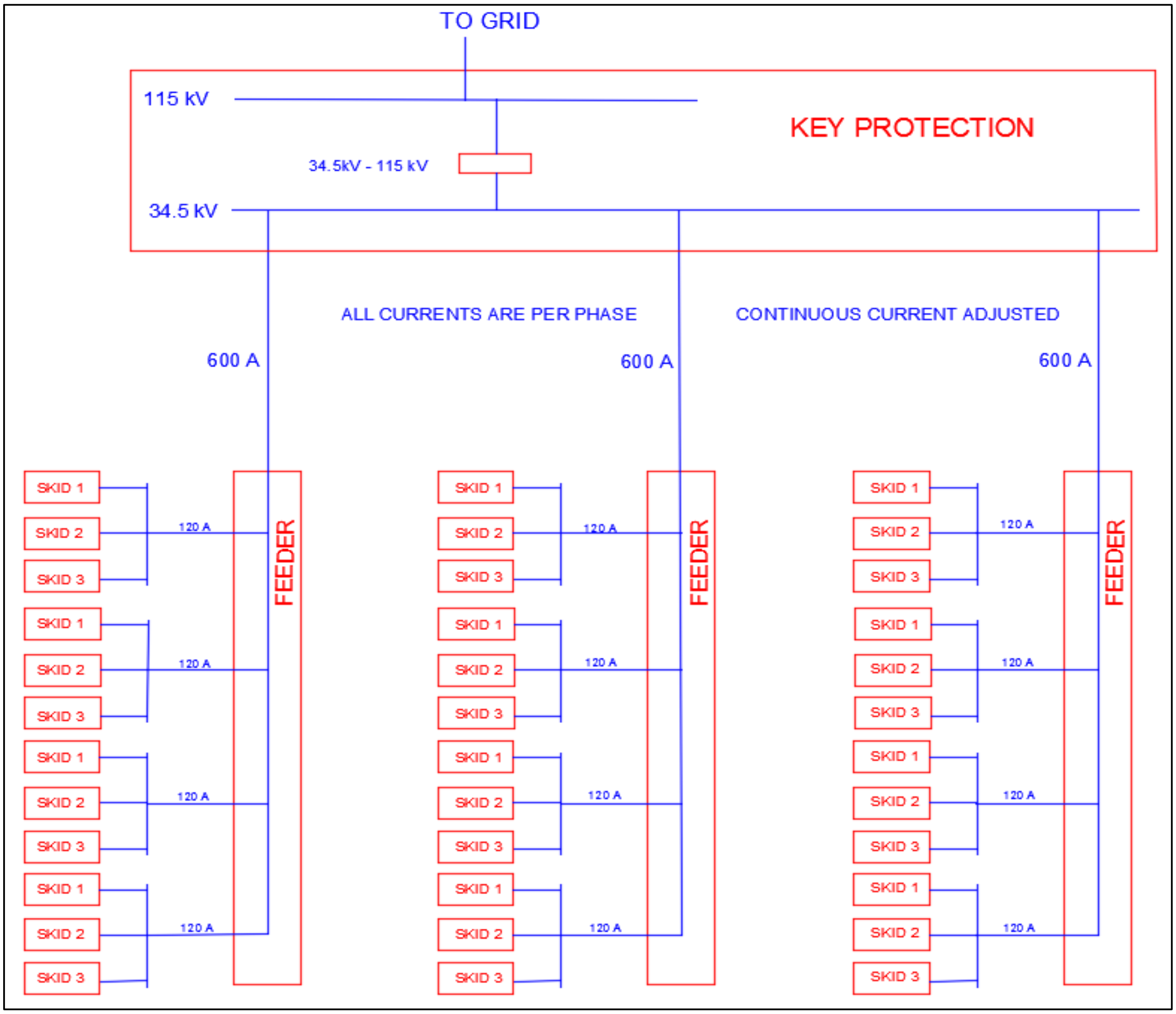


Figure 4. Substation Power Flow Block

2.3.1 Substation Component Functions

- Primary Transformer – The primary transformer is an 85 MVA that steps up the feeder bus input of 34.5 kV to desired 115 kV
- Current Transformer (CT) – Drops current to manageable level for relay, usually between 1 and 5 amps.
- Circuit Breakers – A device in key protection that opens the feeder switch when relay detects an overcurrent condition.

- Relays – Relays are monitoring devices used to detect ground fault currents and reduce saturation. If there is an overcurrent fault they command the circuit breakers to open the circuit. Once current reverts to normal level, the relay will command the circuit breaker closed.
- Capacitor Bank – The 9.0 MVAR capacitor bank stabilizes harmonics associated with three-phase currents and helps maintain a power factor of 0.95. Component specifications were provided by utility and Black & Veatch.
- Surge Arrestor – Surge Arrestors are devices that are used to maintain equipment protected from overvoltage transients caused by lightning strikes, or switching over voltages within the substation itself. In this project they are used to protect the four terminals going into each of the three feeder transmission lines.

3 LOW LEVEL DESIGN

This section will focus on detailed design elements. Components for both the solar and substation component will be explained in detail. The design conditions for the 60 MW power plant are based on a central Iowa solar radiation patterns.

3.1 Solar Component Design

In this section, the low level solar design aspect will be thoroughly explained. It is important to consult the array parameter tool, figure 6, during the entire solar design aspect.

A string consists of 28 modules (or panels) are connected in series. Two strings in parallel constitute a rack. A total of 12 racks will be combined in parallel at the combiner boxes. The simplified rack to transformer current path is shown in figure 5.

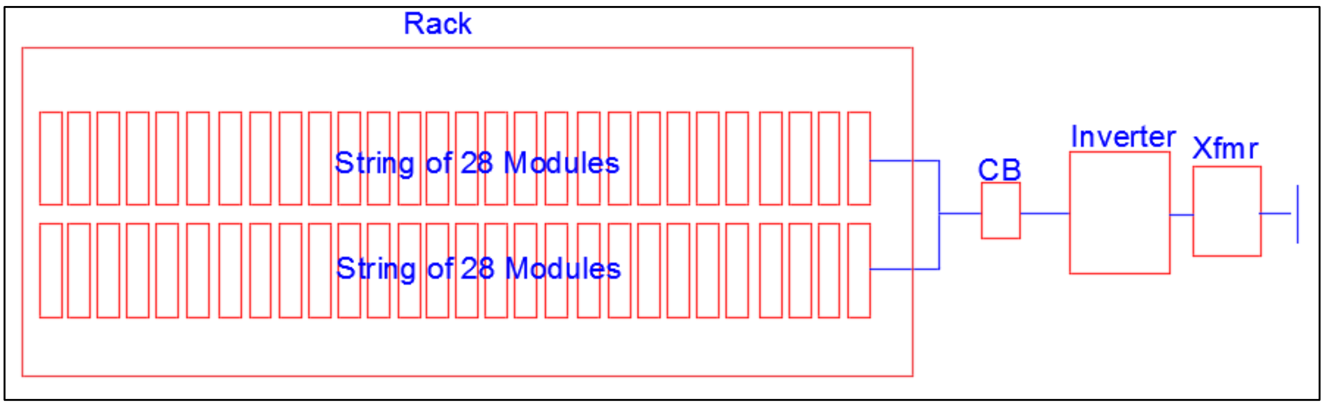


Figure 5. Simplified Array Power Flow Diagram

3.1.1 Array Parameters

Here we will use an array parameter tool (figure 6), is an Excel spreadsheet provided by Black & Veatch and modified by the team, to assist in designing the solar array layout. Taking into consideration panel parameters, string parameters, current output, combiner box capacity, inverter capacity, ILR, and irradiance correction factor, and continuous current correction. The panels used are Hanwha QCELLS Q Plus L-G4.1 325 W solar modules (see *Appendix* for specification sheet). The efficiency of the panels is 16.3%.

	String Size				**Electrical Rack Size**				**CB capacity**		
	Min Temp	-26	C		Module width	3.28	ft		Module/string Isc (series)	9.44	A
					module height	6.54	ft		Isc continous current multiplier	1.25	see (a)
	Voc	46.43	V						Nom Isc	11.8	A
	Ref temp	25	C		Rack width	28	modules		Isc irradiance correction	1.25	see (b)
					Rack height	2	modules		Max Isc string	14.75	A
	Temp Coeff of Voc	-0.0029	per deg C						Max Isc rack, at CB	29.5	A
	Temp delta	-51			Rack width	91.84	ft		Allowed current CB	400	A
	temp correction	1.15			Rack height	13.08	ft		Max current per CB	354	A
	Voc corrected	53.297							Strings per CB	27.118644	
					Frame width	1.38	in		Number of CB per array	11	
	String voltage/CB in vol	1500	V						Actual strings per CB	24	****
	String size	28.14417									
	string size (series)	28	modules								
	String voltage calculate	1492.3	V								
(a)	NEC690.8(B)(1) requires overcurrent device ratings shall not be less than 125% of the maximum currents calculated.										
(b)	NEC690.8(A)(1) requires another 125% correction multiplier before the applicaton of other correction factors.										
	The irradiance correction factor is a multiplier for the current output of a solar panel. Panels can have power spikes with higher solar irradiance.										
	Thus the total current correction factors are 156%										
(c)	The total component area includes the racks and inverter skid. Does not include negligable area of converter boxes or recombiners. (rack area)(118)+(inv skid area)										
(d)	Referenced from true north. Azimuth is measured clockwise from true north to the point on the horizon directly below the object.										
**	Access road included										
***	Assumes 6x6 configuration & 16 ft spacing between arrays.										
****	Ecept CB6 and CB7 ,see CB & Inverter Sheet (this xlsx)										

	Array Design				**Array Size**				**Plant Totals**		
	Racks per row	6			Tilt		15	Degrees	Array Blocks	36	
					Azimuth		180	Degrees see (d)			
	Rows per block	20			Rack height proj		12.63431	ft	Number of CBs	396	
	Racks removed	2			Row spac		12	ft	Inverters	36	
	Total Racks	118			Pitch		24.63431	ft	Modules/Panels	237888	
	Total modules in Array	6608			Array height		492.6862	ft	Total Strings	236	
									Total Racks	472	
	Module DC capacity	325	W		Array width		551.04	ft	AC Plant Output	59.976	MW AC
									DC Array Output	77.314	MW DC
	DC capacity	2147.6	kW		Access road width		16	ft			
					Array Size with access road & spacing:				PV Plant Height	3132	ft ***
	Inverter capacity	1666	kW			Array height	508.6862	ft **	PV Plant Width	3386	ft ***
	Inverter S capcity	1831	kVA			Array width	551.04	ft			
	ILR ->Inv in/Inv out	1.289076				Array Area	280306.4	ft^2	Solar Plant Area	10605349	ft^2 ***
							26041.32	m^2		0.380	mi^2
	CB's per Array	11			Inverter skid		22 x 8.5	ft		243.5	acres
					Inverter skid area		187	ft^2		985269.1	m^2
	Power per CB	195.2364	kW		Area of components		141936.5	ft^2			
	Power per Rack	18.2	kW		Ground Coverage Ratio (GCR)		0.506362	see(c)			

Figure 6. Array Parameter Tool

3.1.1.1 Correction Factors

The parameter tool allows efficient string and rack current calculation with the necessary 125% continuous current multiplier in accordance with NEC 690(B)(1). Also, a second safety factor called the irradiance correction factor is utilized as a failsafe for current spikes a string may experience in times of exceptionally high solar radiation. This factor is also valued at 125% of calculated current. See figure 5. The figure also contains mechanical module specifications.

The minimum temperature in figure 6 is an absolute minimum temperature recorded in central Iowa (data provided by ASHRAE). Temperature is an important aspect of solar power generation because open circuit voltage varies greatly with the temperature of the panels. The temperature coefficient of open circuit voltage is the rate of voltage rise per degree Celsius, solar cell open circuit voltage rises as temperature decreases.

3.1.1.2 String Voltage

After determining the open circuit voltage for each module, we calculated the string size of 28 modules in series to stay under the 1500 VDC requirement under absolute extreme conditions. The actual calculated value is 1492.3 VDC.

3.1.1.3 Combiner Boxes

The series string current needs to be no more than 400 A with all correction factors taken into consideration. 400 A is the manufacturer specified limit for the combiner box current. The standard test condition (STC) module current is 9.44 A. Applying the correction factors, NEC mandated continuous current and irradiance correction factor, thus increasing the design calculated string maximum short circuit current from 9.44 A to 14.75 A (Max Isc string) and the maximum rack short circuit current to 29.5 A (Max Isc rack). Applying the correction factors to the CB output we calculate 354 A.

Not all the CBs will have 354 A output, due to placement limitation. As seen in figure 3, no CB is crossing the inverter. Therefore, CB6 will have 6 rack inputs (177 A), and CB7 will have 4 rack inputs (118 A). See figure 7 for details. The combiners will be pole mounted next to the racks.

Combiner (CB)	Strings In	Racks In	Per CB Output (A)
CB1	24	12	354
CB2	24	12	354
CB3	24	12	354
CB4	24	12	354
CB5	24	12	354
CB6	12	6	177
CB7	8	4	118
CB8	24	12	354
CB9	24	12	354
CB10	24	12	354
CB11	24	12	354
		Total Inverter	3481

Figure 7. CB I/O Detail

3.1.1.4 Conductors and Fuse Protection

The conductor selection is based on correction scaled currents as discussed in 3.1.1.1. The string conductor is preselected by the module manufacturer. Fuses are selected based on maximum current calculations. The maximum calculated currents from array parameter (figure 6) and selected conductors are listed in figure 8.

The string conductors and jumpers will be open air. DC feeder conductor will be buried at least 30 inches, measured from top of conductor, as per NEC310 Table 300.50.

Conductors	Max Isc (A)	Type	Material	AWG
String Conductor	14.75	Free Air	Copper	12
Rack to CB - Jumper	29.5	Free Air	Copper	10
CB to Inverter - DC feeder	354	Buried	Aluminum	700
Conductors	Cable Rating (A)	Minimum Depth	Temp (degC)	Fuse
String Conductor	35	NA	75	15
Rack to CB - Jumper	50	NA	75	30
CB to Inverter - DC feeder	375	30 inch	75	355

Figure 8. Conductor Specifications

3.1.1.5 Inverter and Step-Up Transformer

The inverter (see specification sheet in *Appendix*) has 11 CB DC inputs, totaling 2147.6 kW. The inverter output will be 1670 kW, 357 Vac 3-phase via direct throat connection to a matching 1831 kVA step-up transformer. The transformer output is 34.5 kV. The transformer high side is fed to the collector arrangement.

3.1.1.6 Tilt Angle and Azimuth

The solar module tilt angle is determined through multiple simulation runs with HelioScope. Tilt angle is dependent on terrain, latitude and weather pattern to a small degree. The optimal angle for the selected area in Boone is 15%. Note, this will change based on terrain inclination. While the azimuth of 180 degrees with respect to true north implies mid-day peak load, this angle was chosen with the Iowa State University peak power usage for a reference.

3.1.2 Solar Array Layout

This section will explain the full solar plant layout.

3.1.2.1 Single Solar Array Drawing

The following AutoCAD drawing, figure 9, shows the detailed layout of a single array. An array contains 118 solar racks, inverter skid, combiner boxes, and all associated conductors.

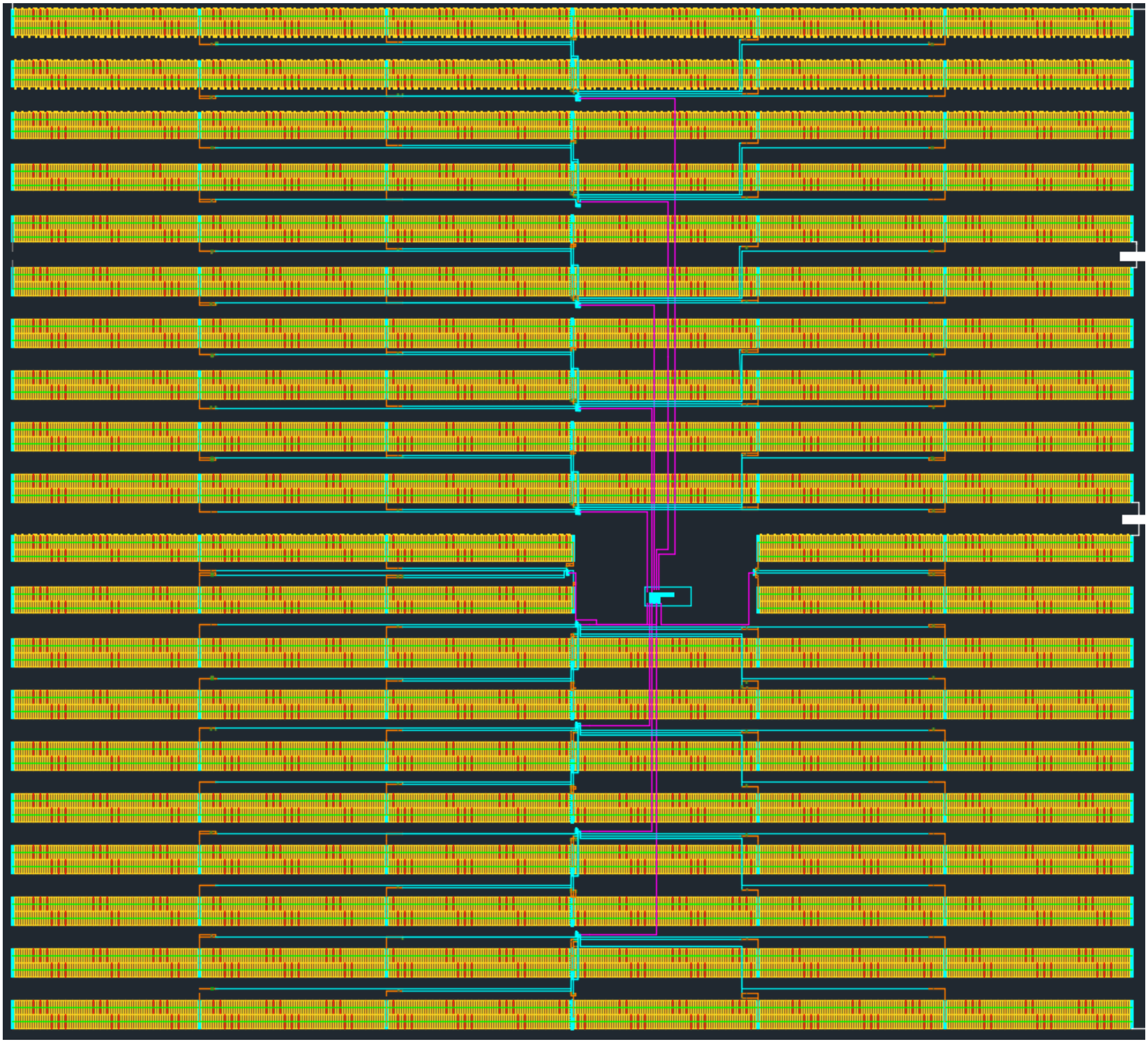


Figure 9. Single Array Drawing

Figure 10 shows the legend and notes section associate with figure 9. Figures 9 and 10 are from MAY1602-W04 AutoCAD file. A single array measures 551.04 ft in width and 493.6 ft in height. The array drawing helps show the scale of an array and conductor routing layout. The light blue conductors are from rack to combiner box (jumpers). The magenta conductors are from combiner boxes to inverter (DC feeders). Also seen in figure 5; each rack feeds into a combiner box, the combiner boxes feed into the inverter. The ground side conductors will run alongside their respective positive side conductors.

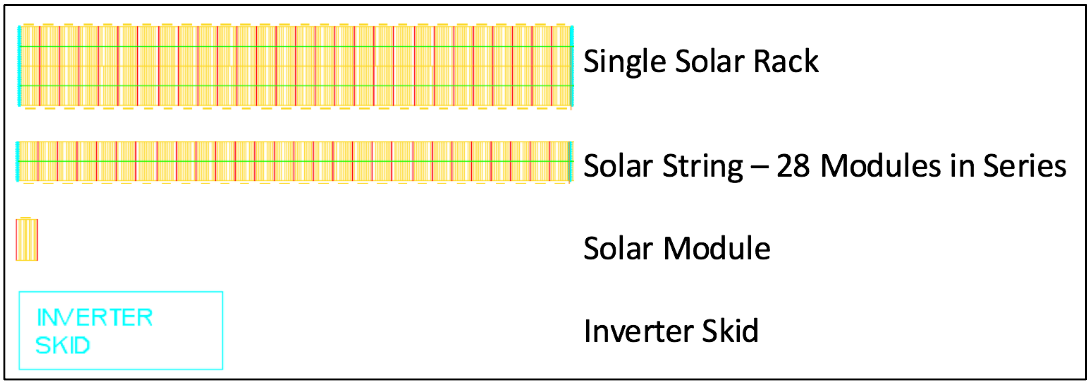


Figure 10. Legend for Figure 9

3.1.2.2 Complete Plant Layout

There are 36 total arrays in the solar plant, the high level overview is shown in figure 11. The 6x6 arrangement is not necessary, it is the most efficient arrangement as it pertains to the conductors. The arrangement is flexible, could be arranged in any manner so long as a straight 16 ft access road is maintained to each inverter skid. The total number of panels will be 237,888.

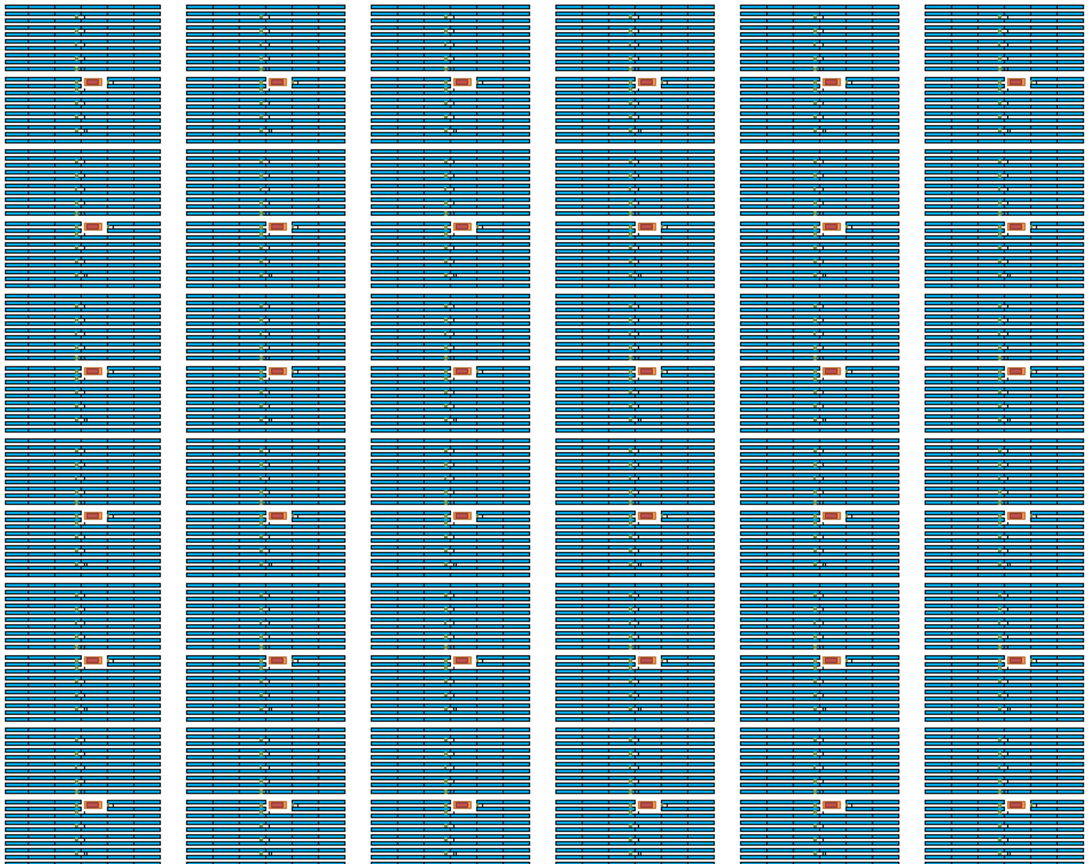


Figure 11. Solar Plant Layout

3.2 Substation Component Design

Power flow through the substation component begins at the collector arrangement, then flowing through 3 feeders the 34.5 kV bus, finally voltage is stepped up and sent to the 115 kV bus. Consult figure 4 for a simplified block. Detailed drawings are provided with the complementary documents outlined in the drawing list.

3.2.1 Collector Arrangement

The collector arrangement is the set of inputs from inverter skid. In this project the component of the collector arrangement consists of the inverter and transformer which sit on an inverter skid. Attached to each of the inverter is a transformer which steps up the voltage to bring it to a sub-transmission level (34.5kV). The collector is not directly located at the substation but is the sum of all the inverter skids (inverters with attached transformers) in each array of the solar power plant. The AutoCAD drawing of the collector (MAY1602-W03 file) illustrates a string, which is made up of 3 inverter skids in parallel and being sent to a select terminal of the feeder. Using 3 1/0 concentric neutral conductors each of these strings to direct to the feeder arrangement. However, the drawing only represents 1 of 12 of these said strings. There are 3 inverter skids per inverter string, see figure 12. There is 4 inverter strings per feeder, see figure 15. And 12 inverter strings total which makes 36 total inputs from 36 arrays.

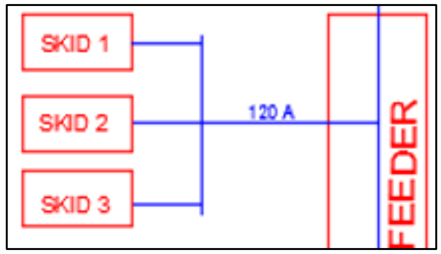


Figure 12. Inverter String in Collector

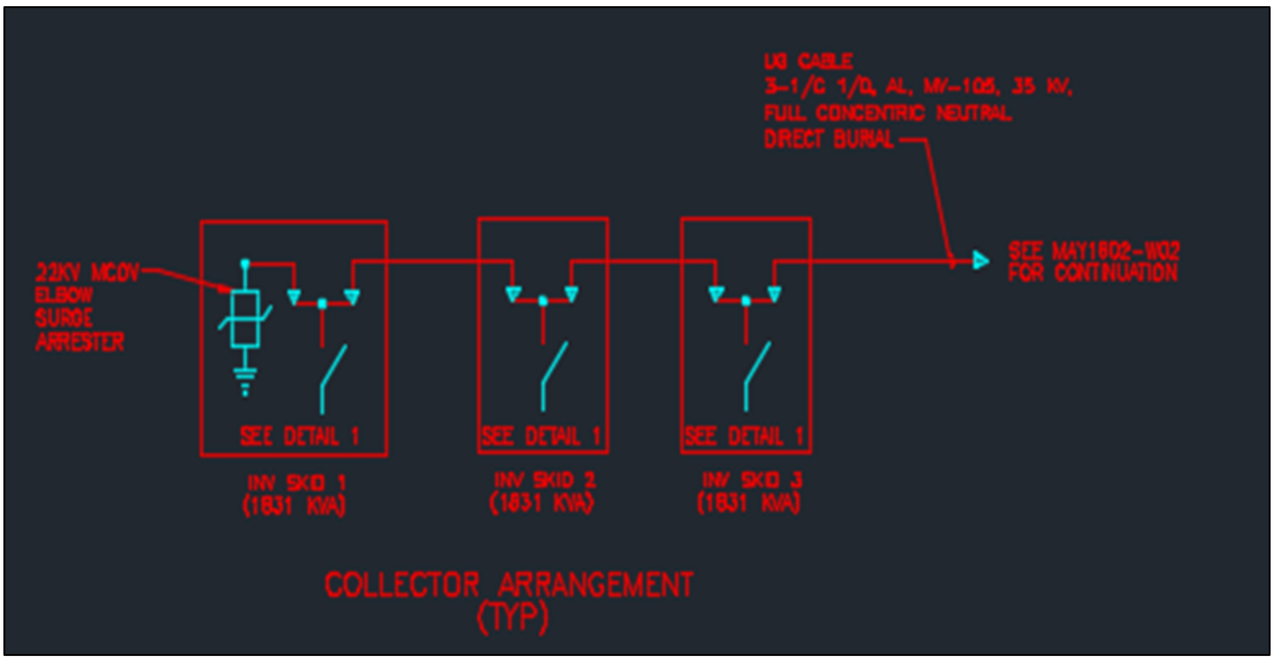


Figure 13. Collector Arrangement

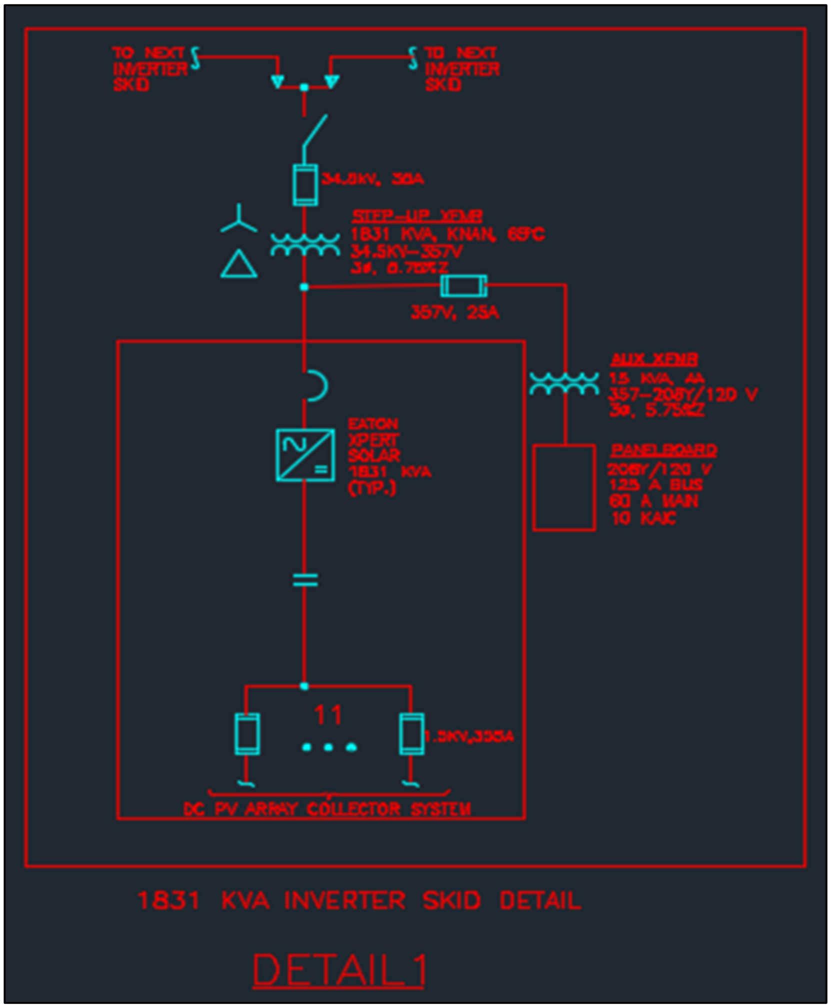


Figure 14. Inverter Skid Detail

3.2.1.1 Surge Arrestor

In this design, there are a total of 12 Surge Arrestors with ratings of 22kV MCOV. The ratings of these surge arrestors were obtained based on section C62.11-1987 in the IEEE standards. Each one of these Surge Arrestors will be attached to three grouped inverter skids, see figure 13. The Collector Arrangement drawing (MAY1602-W02) shows a clear illustration of how a single Surge Arrestor is connected to three Inverters. The main purpose of having Surge Arrestors is to protect equipment in the substation from the maximum continuous voltage experienced due to summing up the current coming from each of the inverters, as well as the unexpected overvoltage caused due to lightning strikes.

Figure 4, shows another representation of how the overall collector arrangement system is connected to the substation through the three main feeders. We can see how there are 4 inputs per feeder and how each of these inputs have three inverters feeding into it.

3.2.2 Feeders

The feeders' role in this system is to group the outputs of the collected power into 3 feeders and then transmit the power to the substation. Each feeder has 4 terminals with attached surge protection (all rated at 22kV) to each terminal and a switch used for line protection. One strings which is made up of three skids (mention earlier in section 3.2.1) is the input of each terminal. Given that there are a total of 12 inverter-transformer skids attached to each of the 3 feeders. Figure 4 shows a representation of the flow of power and how each string of skids is input to each terminal and how each terminal is attached to each feeder line. With there being 4 terminals attached to each of the 3 feeders the current is multiplied by a factor of 4. Therefore, a large cable rating is needed, in this case a 600 KCM ACSR conductor was equipped to each line. See figure 16 for AutoCAD drawing.

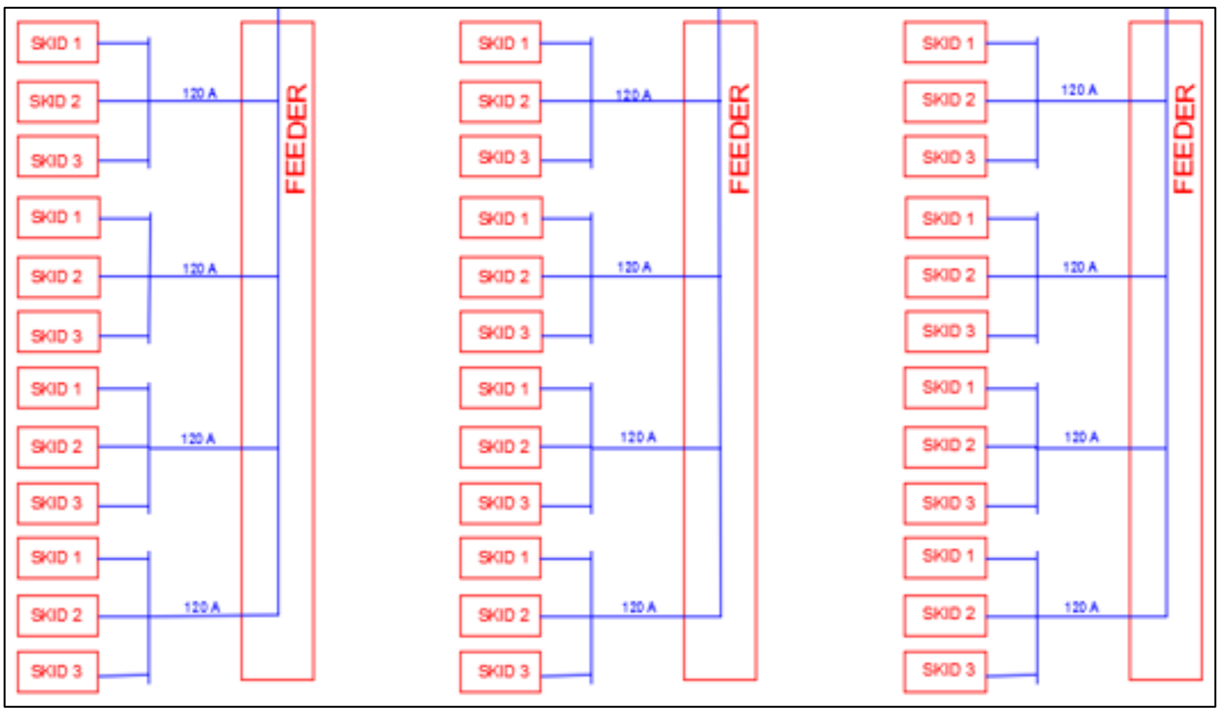


Figure 15. Collector to Feeder Arrangement

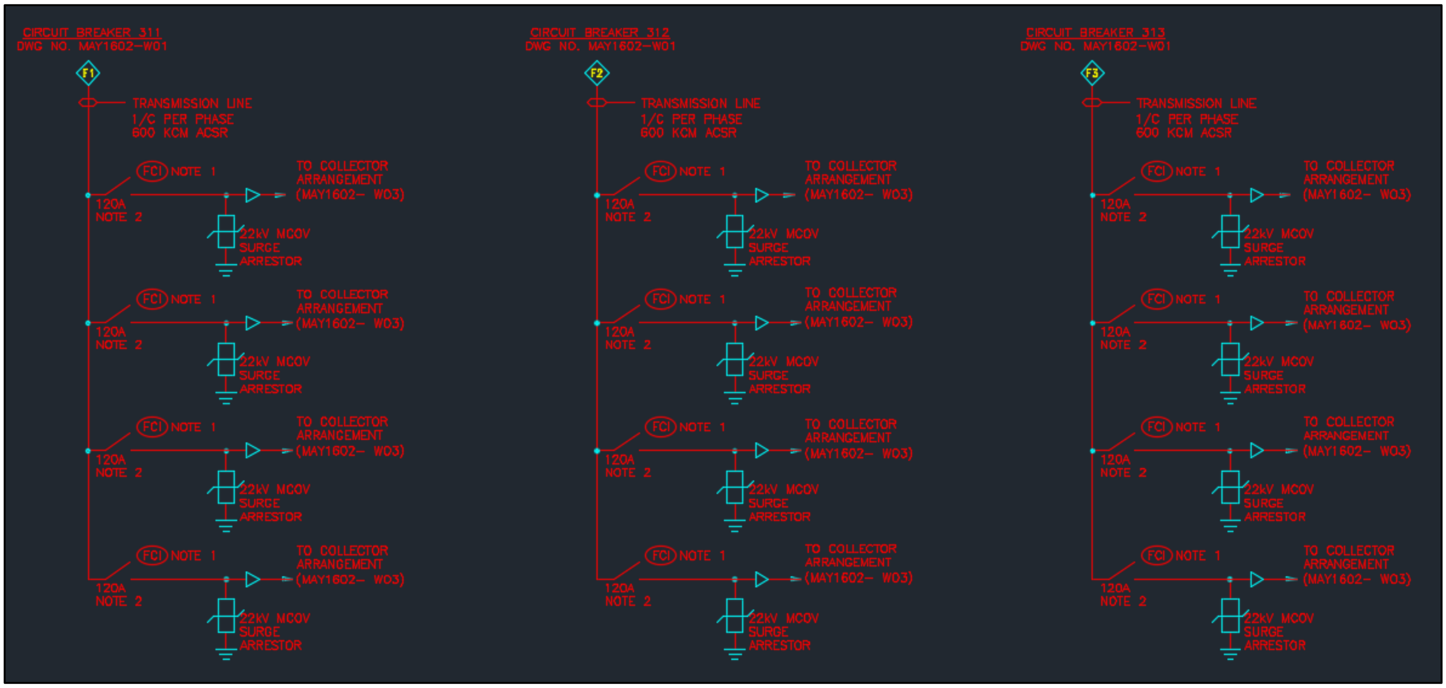


Figure 16. Feeder Arrangement Drawing

3.2.3 Key Protection

Key protection is the bulk of the substation design, nearly all of the protection devices and circuitry is contained in this component. Consult ANSI Standard Device Number Index in the *Appendix* for Device number descriptions. The following AutoCAD drawings are key protection detail. Please note power flow is from figure 20 to figure 19.

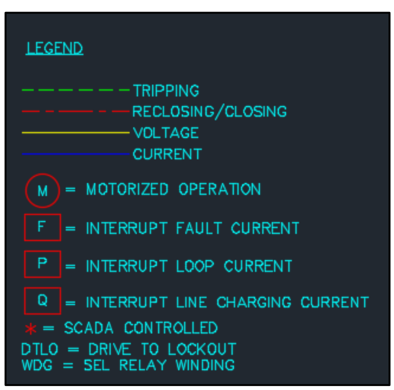


Figure 17. Key Protection Drawing Legend

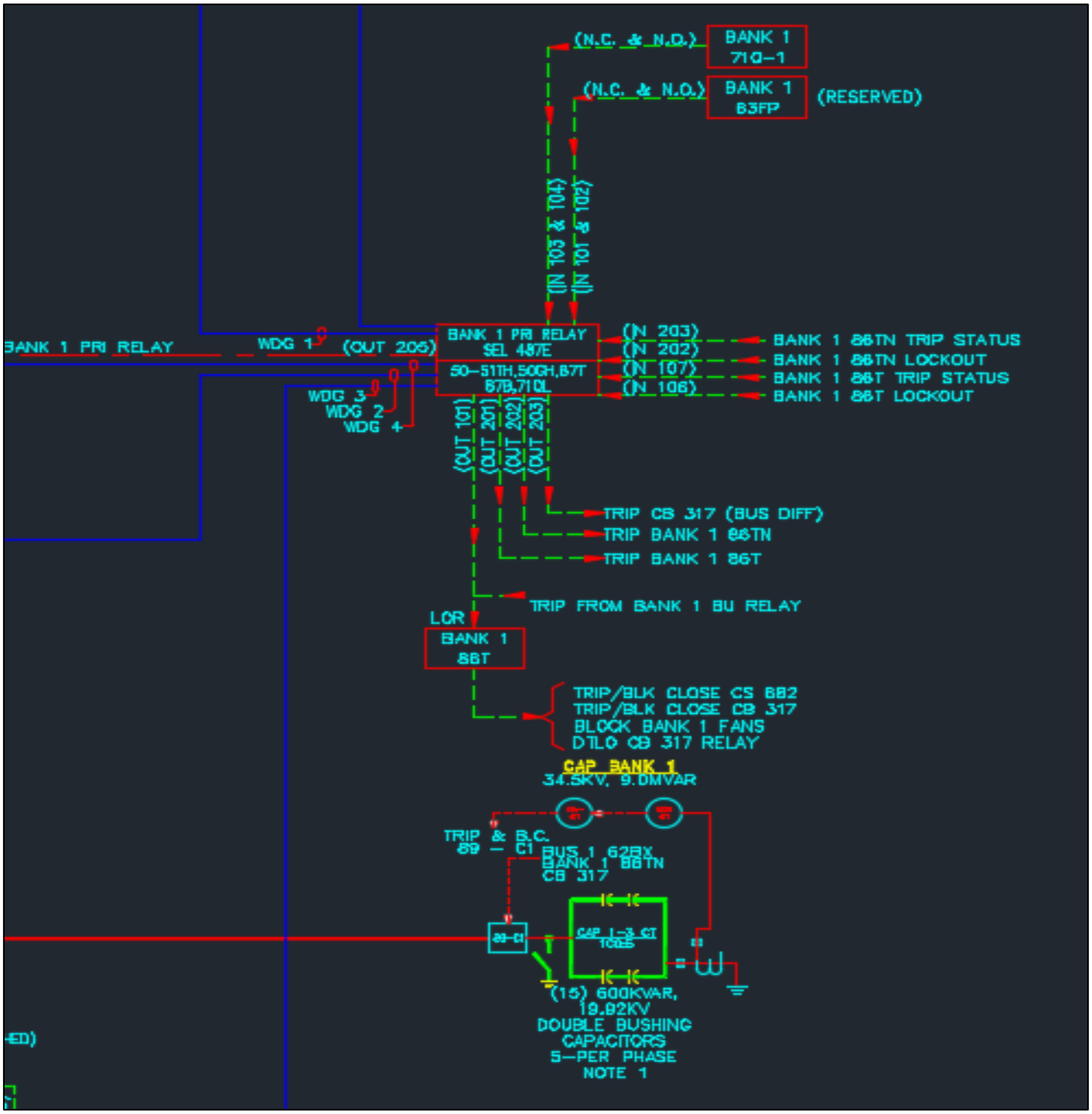


Figure 18. Capacitor Bank Detail.

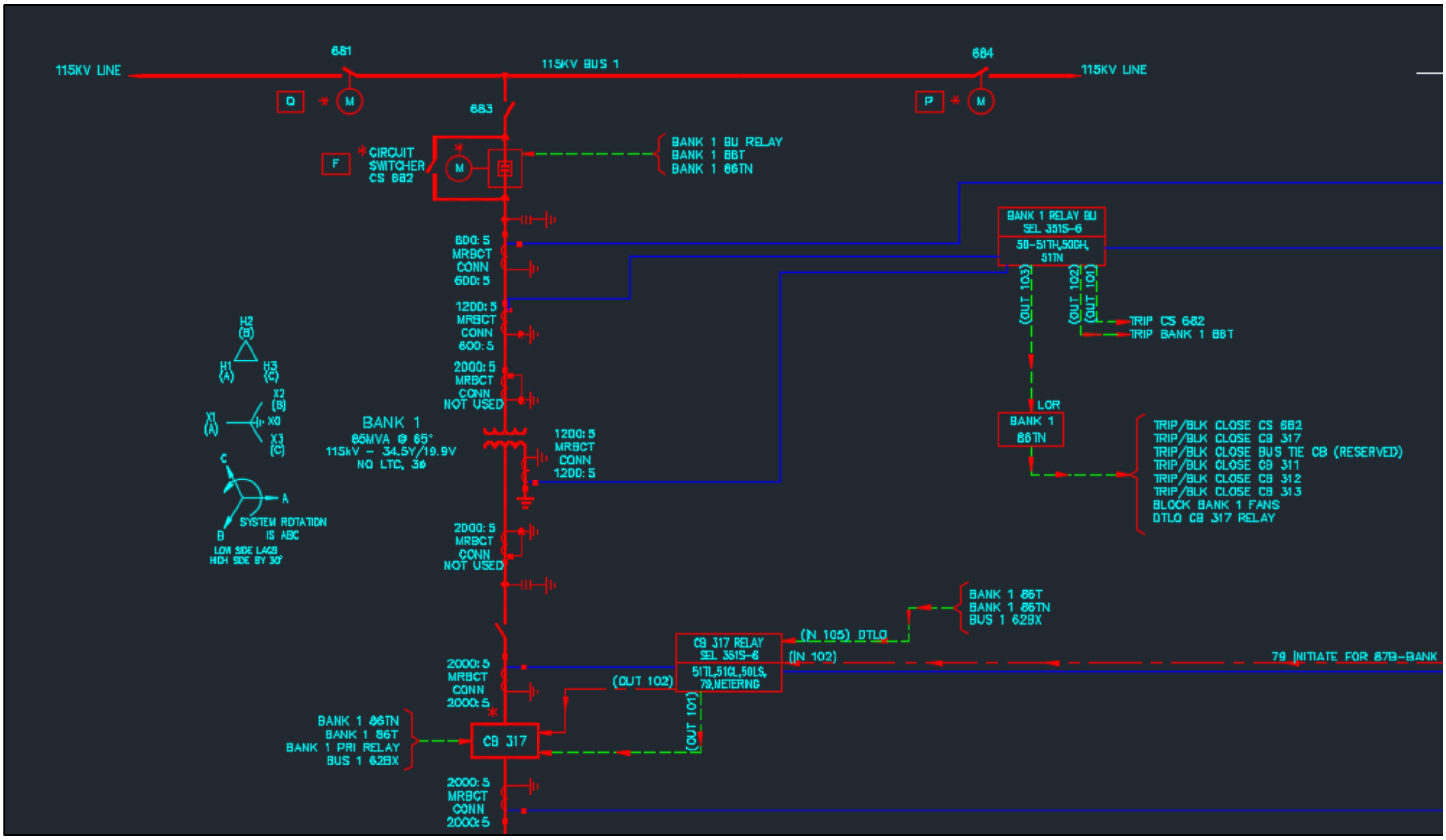


Figure 19. Key Protection 115 kV Bus

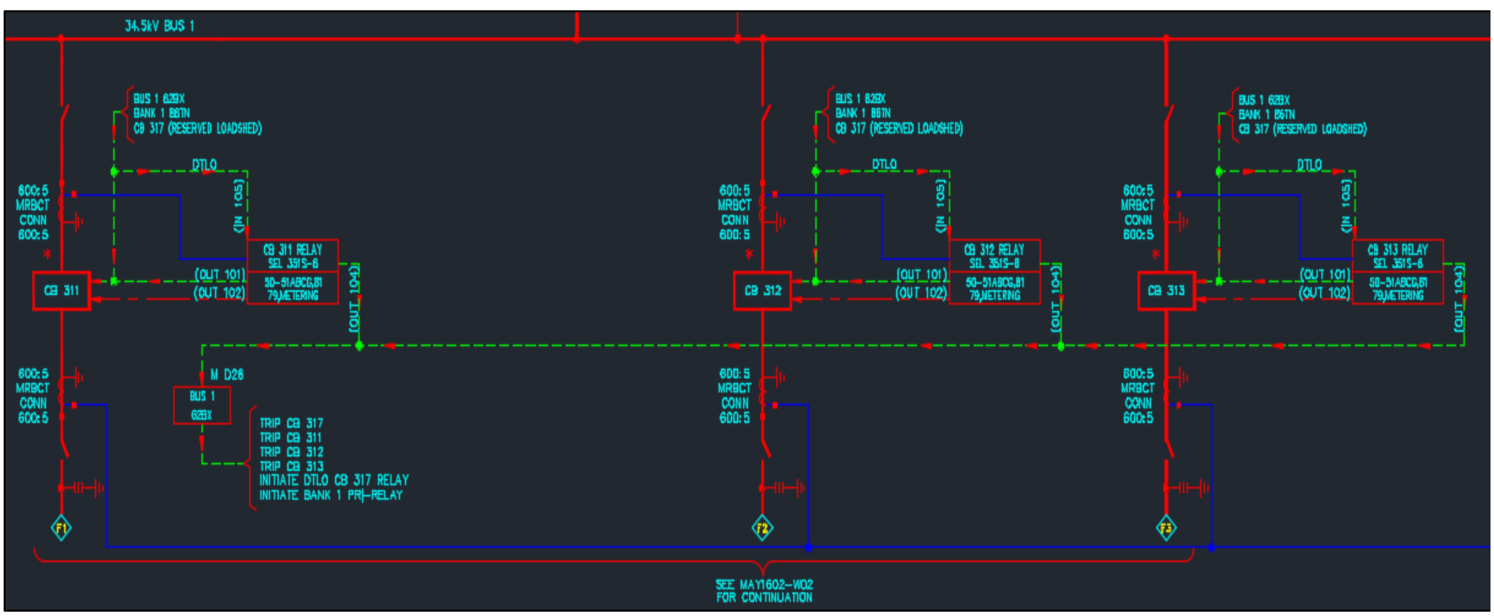


Figure 20. Feeders F1, F2 & F3

3.2.3.1 Relays

In this project we are using 2 different protection relays. The relays act as a central control system for the key protection (MAY1602-W01 file) monitoring the current levels in the feeders to protect the system from faults. They work together to direct the circuit breakers to close or trip depending on the stability of the line. We use five SEL 351S protective relays and one SEL487E (differential relay) relay which is the primary relay.

For our project, we have one 351S relay monitoring each feeder and is positioned ahead of each circuit breaker (CB 311, 312, 313). Each of those relays measure the current after the circuit breaker while relay SEL487E (connected before each circuit breaker) measures the current before each of the circuit breakers and calculates the difference between the two. If an overcurrent is detected, the 351S relays trip the circuit breaker and will not reclose until the current is normalized.

Another 351S relay is monitoring on the higher side of our main circuit breaker (CB 317) with the primary relay SEL 487E measuring the current below CB 317. Once again, it is calculating the difference in the current measurements from each side and looking for over currents. If there are over currents relay SEL 351S will trip and will not reclose the line until it stabilizes.

There is one more 351S relay, which is our backup relay, monitoring on the utility side of the transformer. This provides back up protection and controls circuit switch 682. Each of the switches located on our key protection are also used for maintenance purposes. If a breaker or current transformer needs repaired or replaced, the switches allow us to isolate that part of the line.

3.2.3.2 Current Transformers

Current transformers (CT) are often used to monitor hazardously high currents and reduced them to low currents at high voltages. In this design, we use a multitude of current transformers to help measure the current in a variety of positions in the substation. CT's are specified by their primary to secondary current ratio.

3.2.3.3 Circuit Breaker

A circuit breaker is an automatically operated electrical switch designed to protect electrical circuits. In the case of this project, they are controlled by the protective relays. The relays direct the circuit breakers to interrupt the current flow by tripping the circuit if they detect a fault condition. This will protect the electrical circuitry from serious damage. We use four circuit breakers in our substation, three located on each of the three feeder lines and one on the primary line all with the same purpose of protecting the line and all being controlled by the protection relays. If the relays notices a possible fault, a drive to lockout (DTLO) input is initiated in the relay, followed by the relay outputting an order to the circuit breaker to trip. It will remain tripped until the DTLO input has ended, then the relay will output and order to the circuit breaker to reclose the line.

3.2.3.4 Capacitor Bank

The capacitor bank minimizes harmonics in the three phase system and maintain the power factor of 0.95. The capacitor bank rating of 9 MVAR is determined by running simulations using ETAP software. In the case of this project due to licensing restrictions Black & Veatch provided us with the pf value and capacitor bank rating. See figure 18 for capacitor bank detail. Note, the capacitor bank is connected to the 34.5 kV bus.

3.2.3.5 Primary Line Transformer

The primary line voltage transformer is the main component of the substation and it presents the foremost purpose of having a substation. For this project we are utilizing a step of primary transformer between the two buses, which is stepping up from 34.5 kV to a transmission level of 115 kV.

3.2.3.6 ABS 681/684 Switches

Air-breaker Bypass Switches are manual switches on the high voltage side of the substation transmission line (115 kV). Their main purpose is for maintenance in the transmission line.

3.2.3.7 Communications

The communication components in the substation are mostly made up of the Orion LX Remote Terminal Unit (RTU), a Cisco 2520 Connected Grid Switches and a Cisco 2010 Connected Ground Router. The RTU connects to substation meters, event recorders, distributed I/O, and substation’s protective relays using Fiber and Ethernet connections. While, Cisco’s CGS 2050 and CGR 2010 deploy together to provide a rugged networking solution that enables reliable and secure two-way communication for substation automation.

3.2.3.8 DC Load Center

The Auxiliary DC load center is the most critical protection component of the substation, its primary function is to power the substation’s protective relays and circuit breakers in order to detect and trip faults. It mainly consist of a battery, battery charger, distribution system, switching, protective devices, and monitoring equipment.

3.2.3.9 AC Load Center

The AC load center of the substation is a panelboard consisting of a single panel or a group of panels placed inside one panel. It is usually equipped with switches to control lights, heat, and other power circuits throughout the substation.

3.2.4 Line Currents and Conductors

The conductor detail is specified in the substation AutoCAD drawings. The calculated currents are based on the 1831 kVA step-up transformer on the inverter skid by dividing by the voltage (34.5 kV). All currents are scaled by a continuous current multiplier of 125% as per NEC690(B).

Component	Max Isc (A)	Size	Type
Xformer to Collector / Inverter String	120	1\0 AWG	Concentric Neutral - Buried
Feeder	600	600 KCM	ACSR - Buried

Figure 21. Component Conductors.

3.3 NFPA70 NEC Compliance

The entirety of the system, particularly the solar component design complies with the NFPA70 National Electrical Code. Specific code compliances are referenced throughout this document.

4 PRODUCTION SIMULATION & COST

The kWh production simulation was performed with HelioScope. HelioScope is a thorough simulation that considers monthly average solar irradiation, shading, conductor losses, statistical component mismatch, inverter clipping and soiling. Solar output will be compared to similar systems located in similar latitude and weather settings. The solar panels are rated 325 W nominally at STC, they are capable of producing this at Iowa latitude.

4.1 Annual Solar Radiation

The annual solar radiation data was obtained from NREL. Figure 22 shows the the annual solar radiation monthly in convenient units.

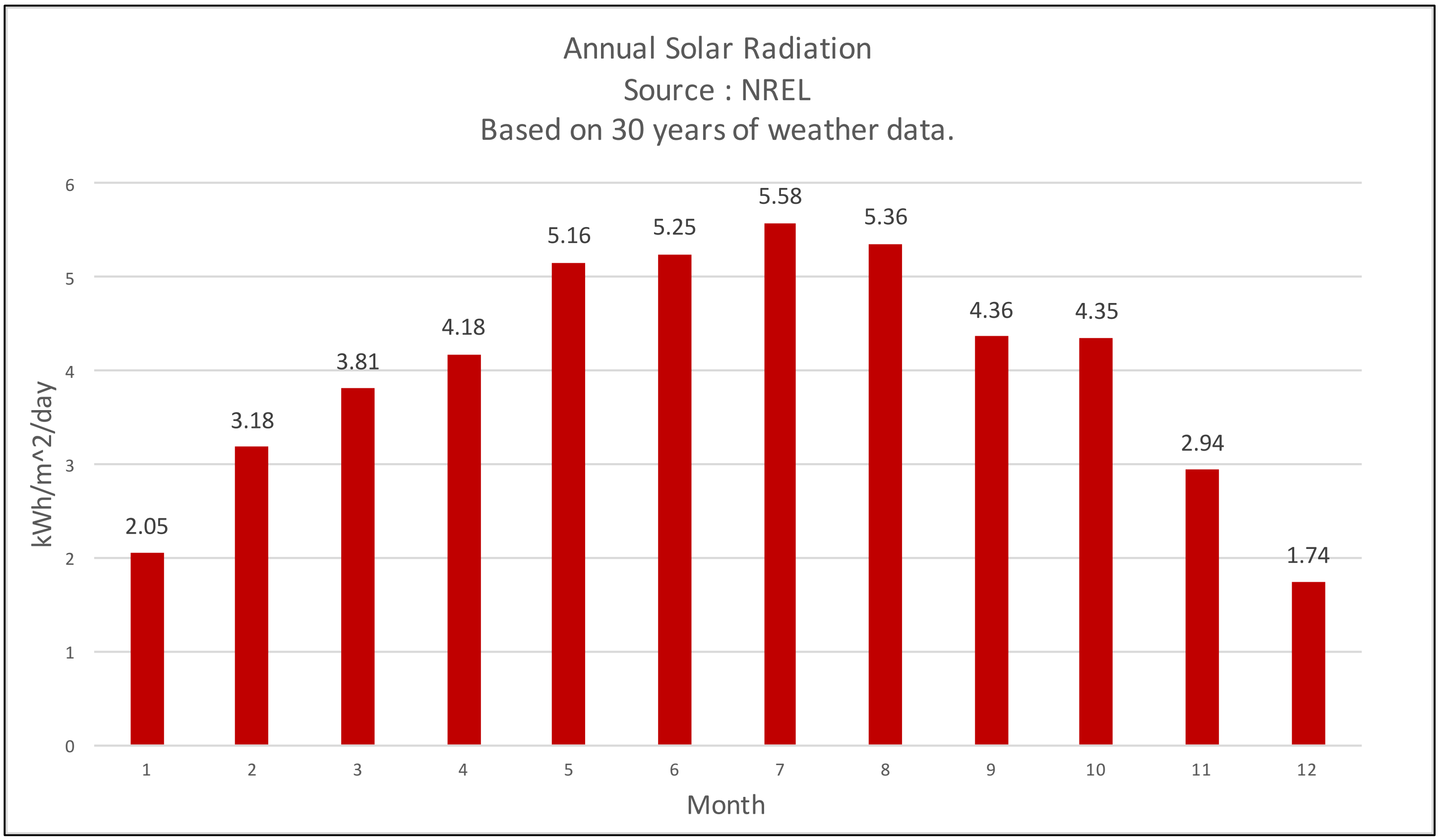


Figure 22. Annual Solar Radiation.

Unsurprisingly we see a pattern of high solar energy density in the summer months with more average sunlight and longer daylight. We can expect the summer to be the most productive period.

4.2 KWH Production

As previously stated, HelioScope was used to layout the solar power plant and provide proper input including the panel specifications, ILR, inverter specifications, step-up transformer specifications, conductor, conductor layout, precise geographic location, weather data from NREL. Weather data is a statistical model forecast based on data thirty years prior. The results are shown in figure 23.

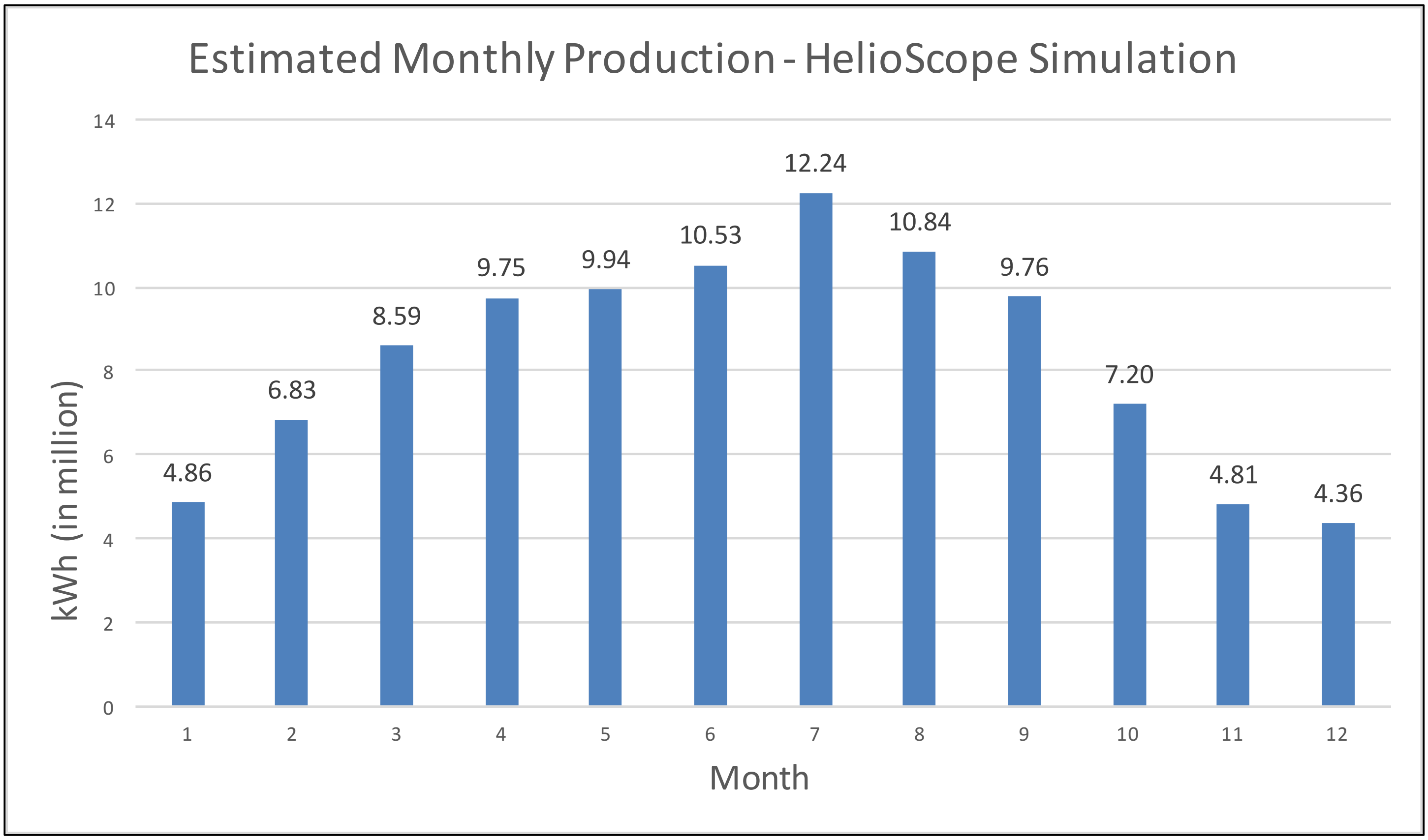


Figure 23. HelioScope Estimated kWh Production.

On an annual basis we have an estimated 97,713,637 million kWh (97.7 GWh). To achieve this amount of production, tuning of the row spacing was needed to minimize shading losses. It has been determined that 12 foot row spacing is the optimal compromise between space saving and minimal shading using HelioScope simulations. Also, with spacing adjustment tuning it was possible to maximize the kWh production in February and October. Thus only three months of the year will have below average production.

4.3 System Losses

The primary production loss is through inverter clipping. This is a compromise between lessening the high solar irradiance production and increasing production during lower solar irradiance. Thus producing a more consistent daily power production. See figure 24.

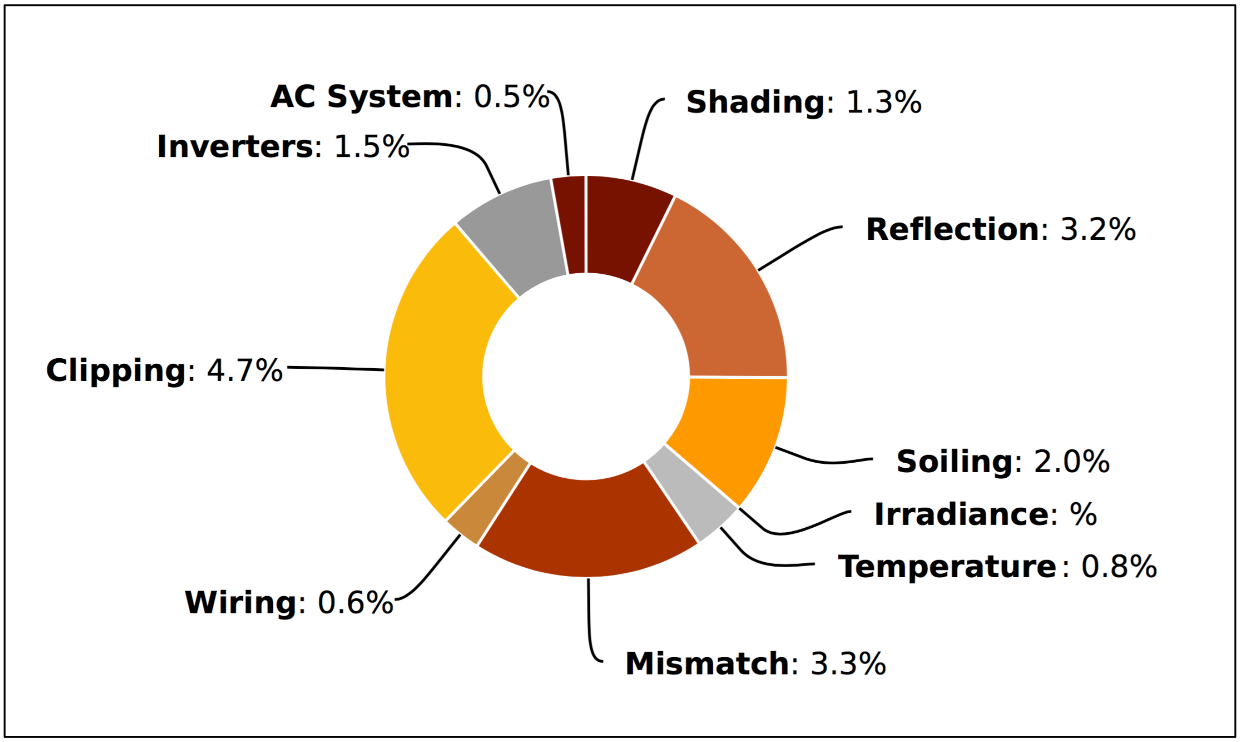


Figure 24. System Losses. Source: HelioScope.

Less obvious sources of losses are explained in the following list.

- **Clipping** – Power loss due to inverter input voltage and output power limits.
- **Mismatch** – Power loss due to component manufacturing defects causing panels to perform out of MPP range. Based on statistical data.
- **Soiling** – Losses due to debris build up from the environment.
- **Irradiance** – Losses due to dusk and evening low solar irradiance causing inverters not to turn on. Using panel tilt tuning, this was reduced to zero.
- **Shading** – Losses caused by shading from rack rows casting shadows onto each other and weather pattern forecasting.
- **Reflection** – Power loss due to reflectivity of panels.

The total system loss is 17.9% of total DC output of 77.3 MW. The loss minimization would have to be tuned for every location.

4.4 Cost

The solar component cost was determined with NREL's PVWatts calculator. While the substation estimate was provided by Black & Veatch. Total cost is about $275,134,800.

4.4.1 Solar Component Cost

The projected cost of the solar component is about $255,134,800, not including any subsidies. This is about $4.25 per MW. For comparison, the Topaz PV Plant cost was $4.53 million per MW.

4.4.2 Substation Component Cost.

Including two transformers, two rows of switchgear, and all other associated components. The cost is about $20 Million.

5 APPENDIX

This appendix contains the definition of terms used throughout this design document, all associated external document links, AutoCAD drawing list, and the original project plan link.

5.1 Glossary of Common Terms

- ILR – Inverter load ratio, the ratio DC input capacity and the inverter AC output capacity, a higher DC input is required to overrun the inverter because the majority of operation the inverter is underrun.
- Irradiance Correction Factor – A multiplier for the current output of a solar panel to compensate for current spikes due to high solar radiation.
- Collector – The substation input from solar array.
- Xfmr or Xformer – Transformer abbreviation.
- CT – Current transformer.
- Feeder – Collector arrangement to 34.5 kV bus.
- Array – A complete unit of solar panels and all associated components including inverters.
- PV – Acronym for photovoltaic.
- PV module/panel – single solar module or panel unit. Module and panel are interchangeable terms.
- STC – Standard temperature conditions, 1000 watts per meter squared irradiation & -25° C.
- Inverter Skid – Base plate for inverter and step-up transformer in an array.
- Jumper – Copper conductors connecting solar modules in series string.
- String – A series combination of modules.
- Rack – Two solar strings in parallel.
- Combiner Box – Weatherproof enclosure for coupling DC conductors with serviceable disconnects, NEC690.16(B).
- Azimuth – Angle between the north vector and the perpendicular projection of the star down onto the horizon.
- MCOV –Maximum Continuous Operating Voltage, maximum designated RMS value of power frequency voltage that may be applied continuously between surge arrester terminals.

5.2 AutoCAD Drawing List

IOWA STATE SENIOR DESIGN TEAM AUGUST 2015 - MAY 2016 115KV/34.5KV SOLAR POWER PLANT/SUBSTATION DRAWING LIST					BLACK & VEATCH PROJECT NO. MAY1602
Task No.	**Drawing Name**	**Drawing Title**	**Revision**	**Date**	**Drawing Status**
1602	MAY1602-W01	KEY PROTECTION 60 MW CAPACITY - SUBSTATION	7	3/2/16	COMPLETE
1602	MAY1602-W02	115/34.5KV SINGLE LINE DIAGRAM 60 MW CAPACITY - SUBSTATION	6	2/29/16	COMPLETE
1602	MAY1602-W03	115/34.5KV AC SINGLE LINE DIAGRAM 60 MW CAPACITY - SUBSTATION	5	2/29/16	COMPLETE
1602	MAY1602-W04	SOLAR ARRAY LAYOUT 60 MW CAPACITY - SUBSTATION	6	3/3/16	COMPLETE
1602	MAY1602-W05	AC SCHEMATIC BANK1 115/34.5KV - PART 1	6	3/24/16	COMPLETE
1602	MAY1602-W06	AC SCHEMATIC BANK1 115/34.5KV - PART 2	6	3/10/16	COMPLETE
1602	MAY1602-W07	DC SCHEMATIC CB 311 FEEDER 1	4	3/11/16	COMPLETE
1602	MAY1602-W08	DC SCHEMATIC CB 312 FEEDER 2	4	3/24/16	COMPLETE
1602	MAY1602-W09	DC SCHEMATIC CB 313 FEEDER 3	4	3/24/16	COMPLETE
1602	MAY1602-W10	DC SCHEMATIC ABS 681 115KV	6	3/24/16	COMPLETE
1602	MAY1602-W11	DC SCHEMATIC ABS 684 115KV	6	3/24/16	COMPLETE
1602	MAY1602-W12	DC SCHEMATIC BANK1 PRIMARY RELAY	4	4/4/16	COMPLETE
1602	MAY1602-W13	DC SCHEMATIC BANK1 BACKUP RELAY	3	4/4/16	COMPLETE
1602	MAY1602-W14	DC SCHEMATIC CB 317 RELAY	5	4/4/16	COMPLETE
1602	MAY1602-W15	DC SCHEMATIC 34.5KV BUS1 BREAKER	2	3/11/16	COMPLETE
1602	MAY1602-W16	DC SCHEMATIC BANK1 ANNUNCIATOR	2	3/11/16	COMPLETE
1602	MAY1602-W17	AC SCHEMATIC BANK1 AUXILIARY	1	3/10/16	COMPLETE
1602	MAY1602-W18	DC SCHEMATIC RTU, ROUTER & ETHERNET SWITCH	1	3/12/16	COMPLETE
1602	MAY1602-W19	DC SCHEMATIC RLH CARD	1	3/12/16	COMPLETE
1602	MAY1602-W20	DC SCHEMATIC DISTRIBUTED I/O MODULE	1	3/24/16	COMPLETE
1602	MAY1602-W21	AC SCHEMATIC MAIN CONNECTION	2	3/24/16	COMPLETE
1602	MAY1602-W22	AC SCHEMATIC YARD & BUILDING LOAD CENTER	2	3/24/16	COMPLETE
1602	MAY1602-W23	DC SCHEMATIC STATION BATTERY, DC LOAD CENTER & 125V BATTERY CHARGER	2	3/24/16	COMPLETE
1602	MAY1602-W24	BUILDING LAYOUT - PART 1	1	3/24/16	COMPLETE
1602	MAY1602-W25	BUILDING LAYOUT - PART 2	1	3/24/16	COMPLETE
1602	MAY1602-W26	BUILDING LAYOUT - PART 3	1	3/24/16	COMPLETE
1602	MAY1602-W27	PANEL ELEVATION - PANEL 101 COMMUNICATION, ABS 681, ABS 684	1	3/24/16	COMPLETE
1602	MAY1602-W28	PANEL ELEVATION - PANEL 103 115/34.5KV BANK 1 PROTECTION & CONTROL	1	3/9/16	COMPLETE
1602	MAY1602-W29	PANEL ELEVATION - PANEL 104 34.5KV BUS CIRCUITS	1	3/9/16	COMPLETE
1602	MAY1602-W30	DC SCHEMATIC 115KV BUS 1 TLS CONTROLLER	2	3/24/16	COMPLETE

5.3 Document and Market Literature Sources

5.3.1 Market Literature Souces

- NFPA 70 National Electrical Code (NEC) 2014 Edition.
- IEEE Standards Association.
- American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) – Solar radiation data.
- Iowa Energy Center – Solar Calculator Tools.
- National Renewable Energy Laboratory (NREL) – Advanced solar radiation data.
- American National Standards Institute (ANSI) – Standard Device Number Index.

5.3.1.1 ANSI Standard Device Number Index

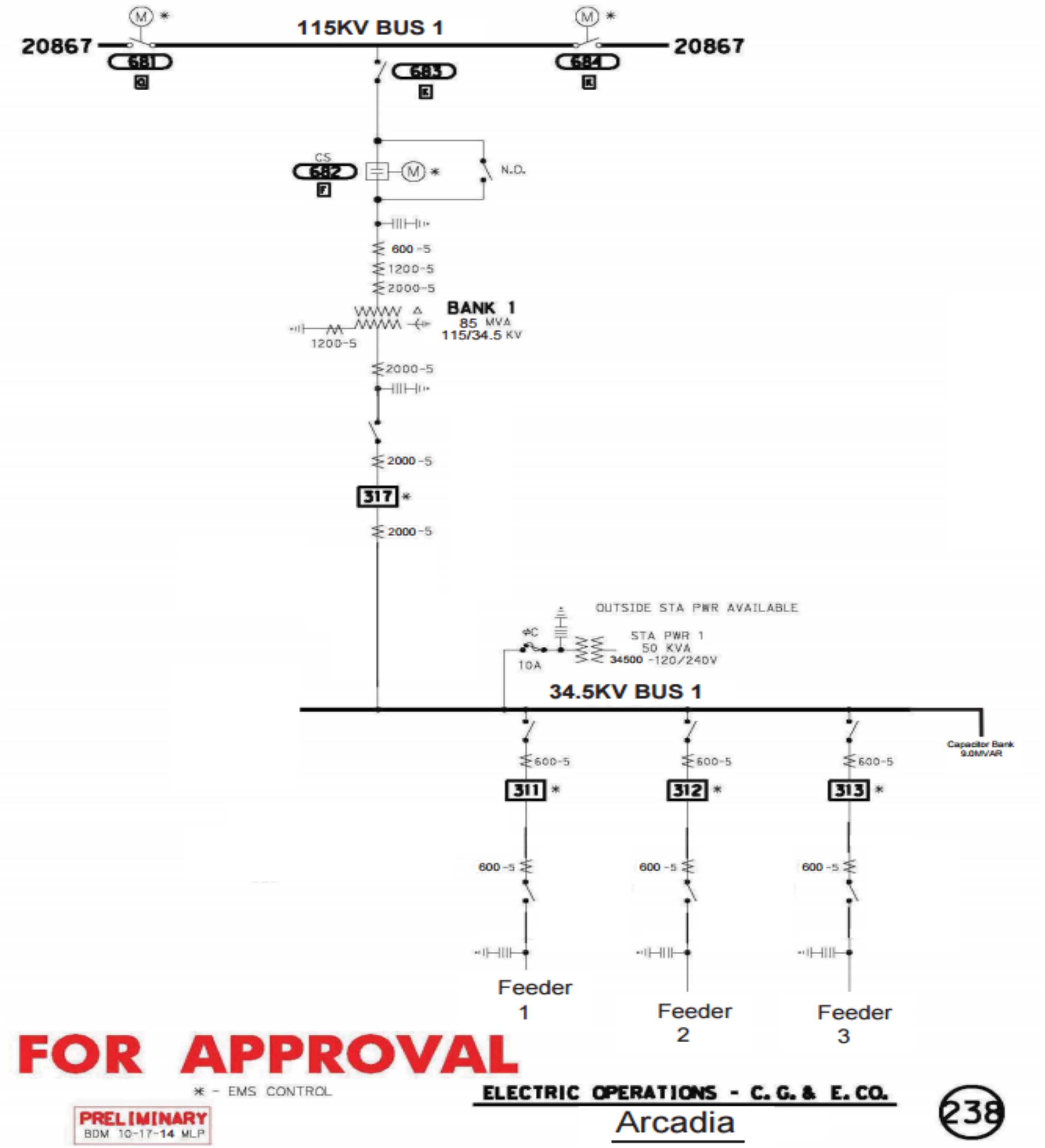
Use for drawing component reference.

INDEX

ANSI Standard Device Number

Device No.	Description	Device No.	Description
1	Master Element	59	Overvoltage Relay
2	Time Delay Starting or Closing Relay	60	Voltage or Current Balance Relay
12	Overspeed Device	61	Machine Split Phase Current Balance
13	Synchronous-speed Device	62	Time-Delay Stopping or Opening Relay
14	Underspeed Device	63	Pressure Switch
15	Speed - or Frequency-Matching Device	64	Ground Detector Relay
21	Distance Relay	65	Governor
23	Temperature Control Device	66	Starts per Hour
25	Synchronizing or Synchronism-Check Device	67	AC Directional Overcurrent Relay
26	Apparatus Thermal Device	68	Blocking Relay
27	Undervoltage Relay	69	Permissive Control Device
29	Isolating Contactor	71	Level Switch
30	Annunciator Relay	72	DC Circuit Breaker
32	Directional Power Relay	74	Alarm Relay
36	Polarity or Polarizing Voltage Devices	75	Position Changing Mechanism
37	Undercurrent or Underpower Relay	76	DC Overcurrent Relay
38	Bearing Protective Device	78	Phase-Angle Measuring or Out-of-Step Protective Relay
39	Mechanical Conduction Monitor		
40	Field Relay	79	AC-Reclosing Relay
41	Field Circuit Breaker	81	Frequency Relay
42	Running Circuit Breaker	83	Automatic Selective Control or Transfer Relay
43	Manual Transfer or Selector Device	84	Operating Mechanism
46	Reverse-phase or Phase-Balance Relay	85	Carrier or Pilot-Wire Receiver Relay
47	Phase-Sequence Voltage Relay	86	Lockout Relay
48	Incomplete-Sequence Relay	87	Differential Protective Relay
49	Machine or Transformer Thermal Relay	89	Line Switch
50	Instantaneous Overcurrent	90	Regulating Device
51	AC Time Overcurrent Relay	91	Voltage Directional Relay
52	AC Circuit Breaker	92	Voltage and Power Directional Relay
53	Exciter or DC Generator Relay	94	Tripping or Trip-Free Relay
54	High-Speed DC Circuit Breaker	95	Reluctance Torque Synchrocheck
55	Power Factor Relay	96	Autoloading Relay
56	Field Application Relay		

5.3.2 Arcadia Substation One-Line Diagram



5.4 Component Specification Sheets

5.4.1 Hanwha QCELLS Q Plus L-G4.1 325 W

http://www.q-cells.us/uploads/tx_abdownloads/files/Hanwha_Q_CELLS_Data_sheet_QPLUS_G4_270-280_2015-04_Rev02_NA.pdf

5.4.2 Eaton Xpert 1670 kW Inverter and Transformer

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0ahUKEwjmnNHTgI_MAhVIWCYKHSvZAFMQFgglMAE&url=http%3A%2F%2Fwww.eaton.com%2Fecm%2Fidcplg%3FIdcService=GET_FILE%26allowInterrupt=1%26RevisionSelectionMethod=LatestReleased%26no

5.4.3 Combiner Boxes

http://www.solarbos.com/data/files/60/2016 SolarBOS 1500VDC Solutions.pdf

5.5 Original Project Plan

http://may1602.sd.ece.iastate.edu/uploads/6/2/1/4/62140729/project_plan_may1602_v3_.pdf