

Final Report SDDEC21-10

Lithium-Ion Energy Storage System (BESS)

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Abstract:

This project was sponsored by Burns & McDonnell to design a Battery Energy Storage System (BESS) for Iowa State University. The BESS system would be designed using the following deliverables, as stated in the SDDEC21 project guidelines: a site layout, system one-line diagram, grounding plan, wire schedule, and power flow and short circuit analysis studies. The overall system design was the most significant feature of this project, and certain issues and concerns were left up to assumptions, such as the specific location and connection to a power drawing station. The design of the Iowa State BESS is an incomplete conceptual model that simulates real-world design practices while implementing industry standards and codes.

Code and Standards Used

NFPA 70 Article 250 Grounding and Bonding

NFPA 70 Article 706 Energy Storage Systems

IEEE 80 AC Substation Grounding

IEEE 3002.2 Load Flow Studies

IEEE 3002.3 Short Circuit Studies

Design Process

Designing a BESS system takes more than just deciding the total amount of required mega-watt capabilities. When designing a BESS system things like location, wire sizing, component selection, grounding, substation sizing and more are needed to take into consideration. To design a BESS that is without a doubt the highest quality, provides the most safety, and ultimately meets the job requirements several steps must be considered. When designing the system code and industry standards must be at the forefront of any design. This requires background knowledge and inductive reasoning to determine that the system is drawn to perfection. To ensure proper design one or two individuals will work on each deliverable from beginning to end. This will ensure that there is an expert on the material derived and someone to double check their work. After a deliverable is ready to be checked the individuals will present it to the team for a peer review session and any updates will be changed to reflect the team's decisions, assumptions, or necessities. After reviewing and making any updates to the deliverable the team will have one final review session to determine if everyone is satisfied the document meets all industry standards as well as job requirements. When the approval is met of the team the deliverable will be passed off to the client for final review and approval. In instances of disapproval the deliverable will be reevaluated for the concerns of the client, reevaluated by the team and resubmitted to our client. When approval is met the individuals will begin working on the next deliverables desired and the process continues. As undergraduate students that have not seen much real world application and design this process is slow with a lot of trial and error resulting in a slow pace of design and lots of learning through client meetings.

EE/CPRE 491 to EE/CPRE 492

Our initial design process from EE/CPRE 491 was finished with the site layout and one-line diagram. These diagrams were approved by our client as finished pieces and required no functional review at the beginning of EE/CPRE 492. Due to certain constraints brought up from

the final presentation of EE/CPRE 491, a new site and or placement of our design was discussed due to a bylaw of building in the central campus. Upon discussion with our client, they were more than willing to express the Cyclone BESS as an undetermined location and continue work as normally scheduled to avoid more time constraints in the future. The specific location was left undetermined since the conceptual design of the site layout was approved and met the functionality requirement of providing two hours of power to Iowa State’s campus in the event of a power failure. Small wording changes were made to the one-line diagram throughout EE/CPRE 492 to help design the wire schedule. No other changes were made to work previously completed in EE/CPRE 491.

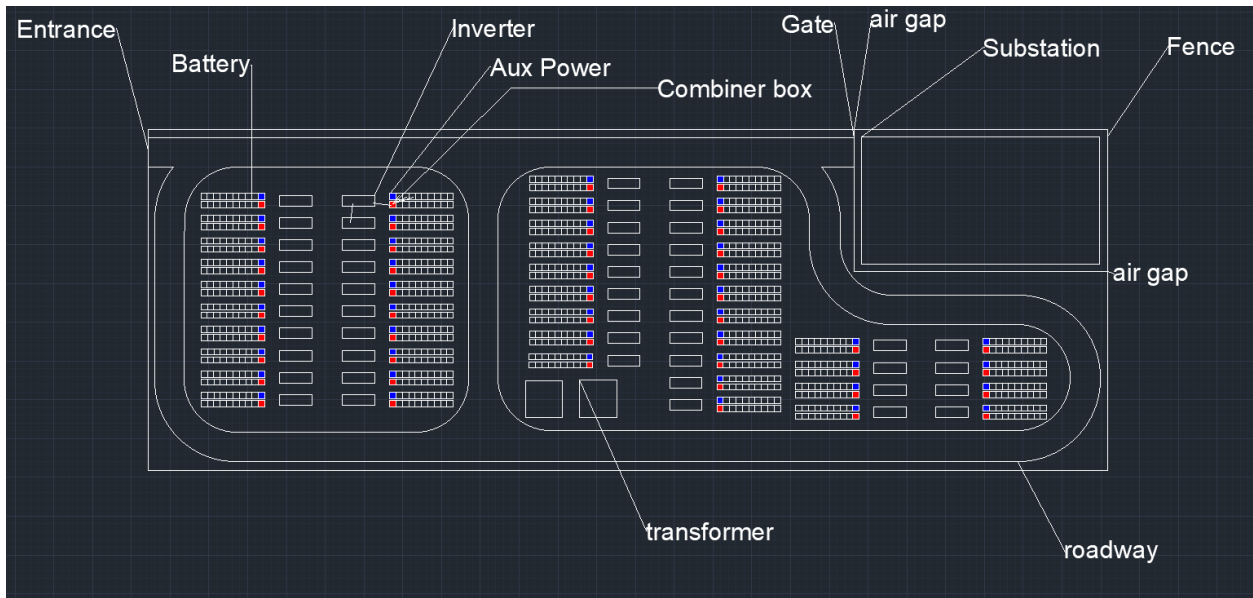


Figure 1: Site Layout

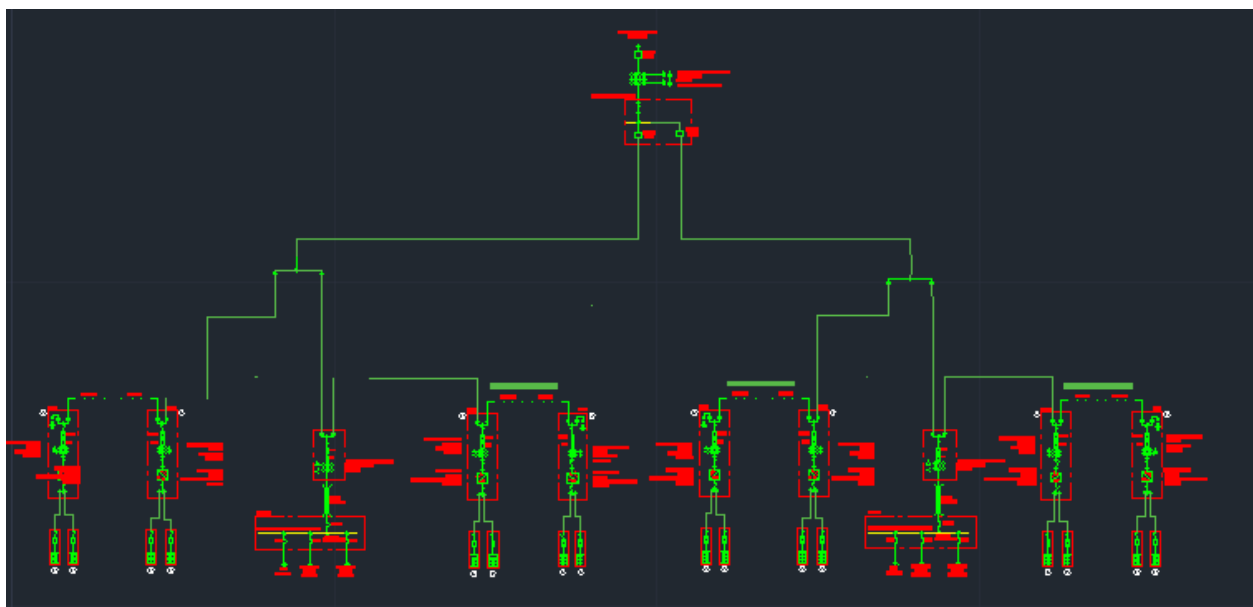


Figure 2: One Line

EE/CPRE 492 Experience

Grounding Plan:

The grounding plan was the first deliverable due during EE/CPRE 492. This plan is a design of the grounding network depicting the overall layout of bare copper wiring below the site, where grounding rods are to be placed, as well as where jumpers would be placed to components. Using industry standards such as: IEEE 80 AC substation grounding, NFPA article 250, and NFPA article 706, a design was constructed and can be seen in **Figure 3** below. The overall design features rows spaced ten feet apart and columns spaced 15 feet apart. Cadwelds are used at each corner and intersection of rows and columns as well as each grounding rod placement. Grounding rods are placed no less than six feet apart and centered around areas of large grounding jumpers. The AC substation has been left without grounding rod placements due to not designing a physical substation layout. Since no layout was designed or required, rods could not be placed to follow industry standards.

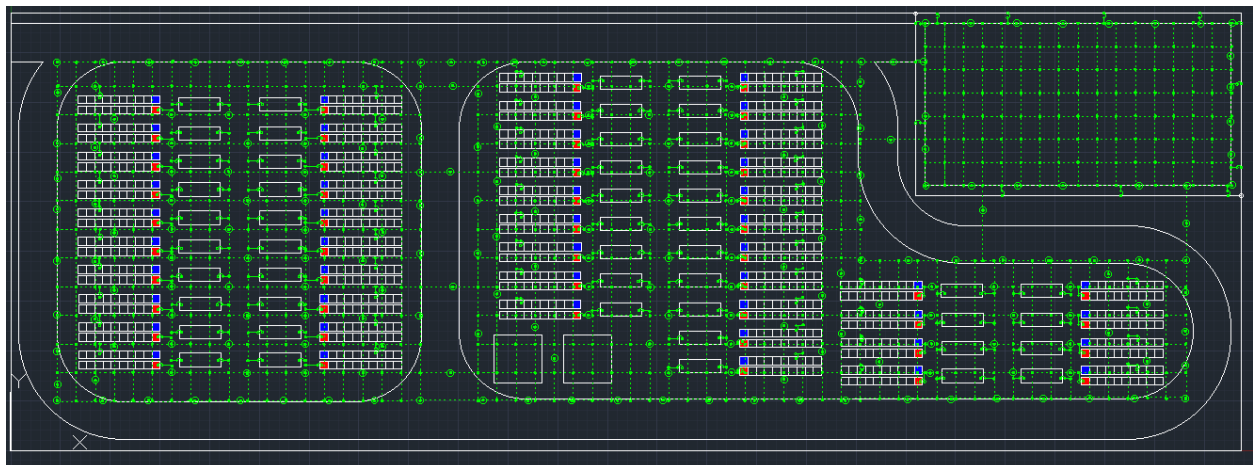


Figure 3 Grounding Plan

Wire Schedule:

The second deliverable of the semester was the wire schedule. This document is the logistical layout of every wire used in our system. The wires begin at battery rack one and combine in series throughout the system. The wires are sized beginning at rack one and the current is added through each following rack to the inverter. This convention allows for the system to handle all of the load or generation of the system through the final components in cases of fault, short, or normal generation. The completed wire schedule can be found in **Appendix A**.

Load Flow and Short Circuit Analysis:

The load flow and short circuit analysis were the final deliverables due this semester. These analysis simulations confirm whether the system we designed can withstand optimal and non-optimal conditions and function as intended. This simulation was done using ETAP, a software that was recommended to us by and used by our client. Using ETAP, a system was designed following the same principles as our one-line diagram construction. This time, during the design process, specific components are used and their parameters are what guide ETAP's simulations. During load flow analysis, ETAP displays the generation or consumption of power along buses depicted by the PCS inverters, transformers, and substations. This depicts how power will be used, either as a load or a generator. During the short circuit analysis, ETAP uses the same principles, but rather than applying the power generated or consumed across a bus, it will short circuit across each component and determine how the current flows, as well as its magnitude in each instance. This test is performed across all possible short circuit potentials.

System Testing

Generally, our design will be tested to determine the functionality as a whole unit, or of 1 of the 18 individual battery and inverter units. Our test can be broken down into individual components like batteries, inverters, transformers, and substations, and power flow analysis can be done at each point. In designing our site layout and one-line diagram, each design will be evaluated for feasibility and tested as such, but these do not involve in-depth problem-solving skills, rather a sense of real-world application. The project will encompass roughly 147525 square feet of space and will have the capability of powering the campus for two hours upon full charge and depletion. The below calculations will guarantee the minimum MWh rating this system will supply.

Total Battery racks: 864

Rated MWh per battery: 0.3727

Total MWh before losses: 322.0128

	Loss percentage	MWh Losses	Useable MWh
Beginning MWh			322.0128
depth of discharge	2.00%	6.440256	315.572544
Aux losses	3.00%	9.4671763	306.1053677
Discharge losses	3.00%	9.183161	296.9222066
DC cable to PCS	0.20%	0.5938444	296.3283622
PCS	2.00%	5.9265672	290.401795
PCS XMFR	1.00%	2.9040179	287.497777
34.5kV collection	0.10%	0.2874978	287.2102793
MPT	1.00%	2.8721028	284.3381765
HV cable to POI	0.20%	0.5686764	283.7695001

Following these power loss calculations, the Iowa State BESS system can provide 283.769MWh which can provide campus power for two hours in case of emergencies and blackouts.

Operation Manual

Designing a BESS system

Site layout:

1. Choose an appropriate site, which should be a large, relatively flat area not prone to flooding
2. Determine the dimensions of the components being used
3. Layout the components in the area, attempting to be as symmetrical as possible, while following IEEE and NFPA standards

One Line Diagram:

1. From the site layout, determine the total number of each component required
2. Create a drawing diagram beginning at the highest voltage level (generally this will be the drawing station and substation)
3. If not already known, determine how much power the system will be drawing (the voltage the system is bringing in, and what level the voltage needs to be stepped down to for the PCS inverters)
4. Draw a single PCS inverter, including its internal main components (PCS transformer, and disconnects)
5. If not already known, find the PCS transformer rating in the PCS spec sheets, and note this next to the transformer
6. Design a battery bank component (this will be the final level of detail, and the lowest level of the component)
7. Connect the PCS to the number of racks supported in the documentation (in our case, two racks are supported)
8. Apply a numbered symbol to represent notes and specifications.
9. All notes should list out how many components are being represented per drawn object

Grounding Plan:

1. Using a copy of the site layout, establish a new layer in AutoCAD or equivalent software, and choose an unused color scheme
2. Beginning in one corner of the design, draw a dashed border around the battery system
3. Beginning with rows, space them out evenly across the dimension of the system, keeping a minimum distance of six feet between them per standard
4. Repeat this previous step with the columns

5. At each intersection, add a symbol to represent a cadweld (in our case this is a solid circle)
6. At each corner of the system, place a grounding rod, indicated by a circle with a solid circle at its center (circle around a cadweld). This will indicate grounding rods
7. Determine grounding rod placements using special design software to ensure there are no step or touch potentials that could cause injury

Wire Schedule:

1. Beginning at the smallest scale component (battery rack), determine the output current from the specification sheets
2. Using the NEC2020 code, find the ambient temperature of the location, and determine the conductor ampacity needed. This will determine the size of the cable needed for the first battery
3. From here, connect each battery in parallel, and sum the currents
4. Wire sizing will involve repeating the process above for each battery rack
5. Once a bank is finished, the same process will be performed for the PCS inverters, using the current derived from the banks
6. Repeat for all PCS inverters on the string
7. Repeat this process one more time for each PCS to Substation

Using ETAP Power flow Analysis and Short Circuit Analysis:

1. Using ETAP, design a system one-line sketch using embedded battery bank design, starting with one bank
2. Within each battery bank, design a single battery rack template. This template will be copied and pasted for every other rack in the system
3. Right click on the battery component and insert the parameters of your battery. These can generally be found from the specification sheets of the chosen battery
4. Once the parameters are specified, you can copy and paste to add the total amount of batteries present in each battery bank
5. Once the batteries are in place, use a DC bus and DC wire to connect all batteries together, and exit back to the main page of ETAP. This is a completed battery bank and this will be copied and pasted again to represent the total number of battery banks the system has
6. Next, add a PCS inverter by dragging an inverter symbol from the right side, and again enter the parameters listed in the specification sheet for the chosen inverter
7. Copy and paste until all inverters are placed
8. Connect the battery racks to the inverters using DC cables

9. Create an AC bus by dragging the component from the right hand side
10. Connect all of the inverters to the AC bus using AC wire
11. From the AC bus connect this to a three-phase substation design (three-phase transformer)
12. Lastly, create a drawing station design that has a thevenin load model

Appendix A:

Wire Schedule



**CYCLONE BESS
WIRE AND CABLE CONDUCTOR SIZING**

ELE-001

	15000 V Power Cables t	1	2	3	4
	1-3/C #2	126	252	378	504
58.7	1-1/C #2/0	210	420	630	840
117.4	1-1/C 250 kcmil	306	612	918	1224
176.1	1-1/C 350 kcmil	362	724	1086	1448
234.8	1-1/C 500 kcmil	426	852	1278	1704
293.5	1-1/C 750 kcmil	508	1016	1524	2032
352.2					
410.9					
469.6					
528.3					
587					
645.7					
704.4					
763.1					
821.8					
880.5					
939.2					
997.9					
1056.6					
1115.3					
1174					
1232.7					
1291.4					
1350.1					
1408.8					
1467.5					
1526.2					
1584.9					
1643.6					
1702.3					
1761					
1819.7					
1878.4					
1937.1					
1995.8					
2054.5					
2113.2					
2171.9					
2230.6					
2289.3					
2348					
2406.7					
2465.4					
2524.1					
2582.8					
2641.5					
2700.2					
2758.9					
2817.6					

3.1 POWER CABLE DATA SHEET – AMPACITIES AND AREAS

Based on the NEC, IEEE 835, & ICEA P-54-440

15,000-VOLT POWER CABLE

CABLE TYPES: HEN, HEL, HRN, HRL

CABLE TYPE	CABLE CODE	DUCT AMPACITY	NON-DUCT AMPACITY	AREA (SQ. IN)
1-3/C #2	H2-3	101	126	3.67
1-1/C #2/0	H2/0-1	149	210	1.12
1-1/C 250 kcmil	H250-1	203	306	1.53
1-1/C 350 kcmil	H350-1	235	362	1.77
1-1/C 500 kcmil	H500-1	270	426	2.10
1-1/C 750 kcmil	H750-1	301	508	2.83

5,000-VOLT POWER CABLE

CABLE TYPES: PEN, PEL, PRN, PRL

CABLE TYPE	CABLE CODE	DUCT AMPACITY	NON-DUCT AMPACITY	AREA (SQ. IN)
1-3/C #2	P2-3	98	119	2.24
1-1/C #2/0	P2/0-1	149	205	0.75
1-1/C 250 kcmil	P250-1	203	294	1.03
1-1/C 350 kcmil	P350-1	235	349	1.24
1-1/C 500 kcmil	P500-1	270	423	1.55
1-1/C 750 kcmil	P750-1	301	489	2.02

ALLOWABLE CONDUIT FILL

Cables Per Conduit (% Fill Permitted)

Size (In)	Inside Dia. (In)	2 Cables 31%	3 or More 40%	1 Cable 53%
3/4	0.836	0.170	0.220	0.291
1	1.063	0.275	0.355	0.470
1 1/4	1.394	0.473	0.610	0.809
1 1/2	1.624	0.642	0.829	1.098
2	2.083	1.056	1.363	1.806
2 1/2	2.489	1.508	1.946	2.579
3	3.090	2.325	3.000	3.974
4	4.050	3.994	5.153	6.828
5	5.073	6.266	8.085	10.713
6	6.093	9.039	11.663	15.454

600-VOLT POWER CABLE

CABLE TYPES: SEN, SEL, SRN, SRL

CABLE TYPE	CABLE CODE	DUCT AMPACITY	NON-DUCT AMPACITY	AREA (SQ. IN)
1-2/C #12	S12-2	20	16	0.15
1-3/C #12	S12-3	20	16	0.19
1-2/C #10	S10-2	30	23	0.19
1-3/C #10	S10-3	30	23	0.24
1-2/C #8	S8-2	42	37	0.34
1-3/C #8	S8-3	42	37	0.40
1-2/C #6	S6-2	54	54	0.43
1-3/C #6	S6-3	54	54	0.51
1-2/C #4	S4-2	69	80	0.55
1-3/C #4	S4-3	69	80	0.68
1-2/C #2	S2-2	89	112	0.80
1-3/C #2	S2-3	89	112	0.90
1-2/C #2/0	S2/0-2	131	169	1.31
1-3/C #2/0	S2/0-3	131	169	1.55
1-2/C #4/0	S4/0-2	168	225	1.79
1-3/C #4/0	S4/0-3	168	225	2.14
1-1/C 250 kcmil	S250-1	192	248	0.61
1-1/C 350 kcmil	S350-1	228	311	0.77
1-1/C 500 kcmil	S500-1	273	382	1.00
1-1/C 750 kcmil	S750-1	330	487	1.44
1-1/C 1000 kcmil	S1000-1	372	560	1.80

600-VOLT CABLES

With More Than Three

Current Carrying Conductors

Number of Conductors	Percent of Table Values
4 through 6	80%
7 through 9	70%
10 through 20	50%
21 through 30	45%
31 through 40	40%
41 and above	35%

3.2 IEEE 141: TABLE 3-12 – VOLTAGE DROP

Table 3-12— Three-phase line-to-line voltage drop for 600 V single-conductor cable per 10 000 A-ft (60 °C conductor temperature, 60 Hz)

Load power factor lagging	Wire size (AWG or kcmil)																							
	1000	900	800	750	700	600	500	400	350	300	250	4/0	3/0	2/0	1/0	1	2	4	6	8*	10*	12*	14*	
Section 1: Copper conductors in magnetic conduit																								
1.00	0.28	0.31	0.34	0.35	0.37	0.42	0.50	0.60	0.68	0.78	0.92	1.1	1.4	1.7	2.1	2.6	3.4	5.3	8.4	13	21	33	53	
0.95	0.50	0.52	0.55	0.57	0.59	0.64	0.71	0.81	0.88	1.0	1.1	1.3	1.5	1.9	2.3	2.8	3.5	5.3	8.2	13	20	32	50	
0.90	0.57	0.59	0.62	0.64	0.66	0.71	0.78	0.88	0.95	1.1	1.2	1.3	1.6	1.9	2.3	2.8	3.4	5.2	8.0	12	19	30	48	
0.80	0.66	0.68	0.71	0.73	0.74	0.80	0.85	0.95	1.0	1.1	1.2	1.4	1.6	1.9	2.3	2.6	3.2	4.8	7.3	11	17	27	43	
0.70	0.71	0.73	0.76	0.78	0.80	0.83	0.88	0.97	1.0	1.1	1.2	1.3	1.5	1.8	2.1	2.5	3.0	4.4	6.6	9.9	15	24	38	
Section 2: Copper conductors in nonmagnetic conduit																								
1.00	0.23	0.26	0.28	0.29	0.33	0.38	0.45	0.55	0.62	0.73	0.88	1.0	1.3	1.6	2.1	2.6	3.3	5.3	8.4	13	21	33	53	
0.95	0.40	0.43	0.45	0.47	0.50	0.54	0.62	0.71	0.80	0.92	1.0	1.1	1.5	1.8	2.2	2.7	3.4	5.3	8.2	13	20	32	50	
0.90	0.47	0.48	0.52	0.54	0.55	0.59	0.68	0.76	0.85	0.95	1.1	1.1	1.5	1.8	2.2	2.7	3.3	5.1	7.9	12	19	30	48	
0.80	0.54	0.55	0.57	0.59	0.62	0.66	0.73	0.81	0.88	0.97	1.1	1.1	1.4	1.7	2.1	2.5	3.1	4.7	7.2	11	17	27	43	
0.70	0.57	0.59	0.62	0.64	0.66	0.69	0.74	0.83	0.88	0.97	1.1	1.1	1.4	1.6	2.0	2.4	2.8	4.3	6.4	9.7	15	24	38	
Section 3: Aluminum conductors in magnetic conduit																								
1.00	0.42	0.45	0.49	0.52	0.55	0.63	0.74	0.91	1.0	1.2	1.4	1.7	2.1	2.6	3.3	4.2	5.2	8.4	13	21	33	52	—	
0.95	0.62	0.65	0.70	0.73	0.76	0.83	0.94	1.1	1.2	1.4	1.6	1.8	2.3	2.7	3.4	4.2	5.3	8.2	13	20	32	50	—	
0.90	0.69	0.72	0.76	0.79	0.82	0.88	0.99	1.2	1.3	1.4	1.6	1.9	2.3	2.7	3.4	4.1	5.1	7.9	12	19	30	48	—	
0.80	0.76	0.80	0.83	0.85	0.88	0.95	1.0	1.2	1.3	1.4	1.6	1.8	2.2	2.6	3.2	3.9	4.7	7.3	11	17	27	43	—	
0.70	0.80	0.83	0.87	0.89	0.92	0.98	1.1	1.2	1.3	1.4	1.6	1.7	2.1	2.4	2.9	3.6	4.3	6.5	10	15	24	37	—	
Section 4: Aluminum conductors in nonmagnetic conduit																								
1.00	0.36	0.39	0.44	0.47	0.51	0.59	0.70	0.88	1.0	1.2	1.4	1.7	2.1	2.6	3.3	4.2	5.2	8.4	13	21	33	52	—	
0.95	0.52	0.56	0.60	0.63	0.67	0.74	0.85	1.0	1.1	1.3	1.5	1.8	2.2	2.7	3.4	4.2	5.2	8.2	13	20	32	50	—	
0.90	0.57	0.61	0.65	0.68	0.71	0.79	0.89	1.1	1.2	1.3	1.5	1.8	2.2	2.6	3.3	4.1	5.0	7.9	12	19	30	48	—	
0.80	0.63	0.66	0.71	0.73	0.76	0.83	0.92	1.1	1.2	1.3	1.5	1.7	2.1	2.5	3.1	3.8	4.6	7.2	11	17	27	42	—	
0.70	0.66	0.69	0.73	0.75	0.78	0.83	0.92	1.1	1.1	1.3	1.4	1.6	1.7	2.3	2.8	3.4	4.2	6.4	9.9	15	24	37	—	

*Solid conductor. Other conductors are stranded.

To convert voltage drop to	Multiply by
Single-phase, three-wire, line-to-line	1.15
Single-phase, three-wire, line-to-neutral	0.577
Three-phase, line-to-neutral	0.577
Single-phase, two-wire	1.15