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ENEL 371 DESIGN PROJECT REPORT

FOOD PROCESSING AND PRODUCTION FACILITY

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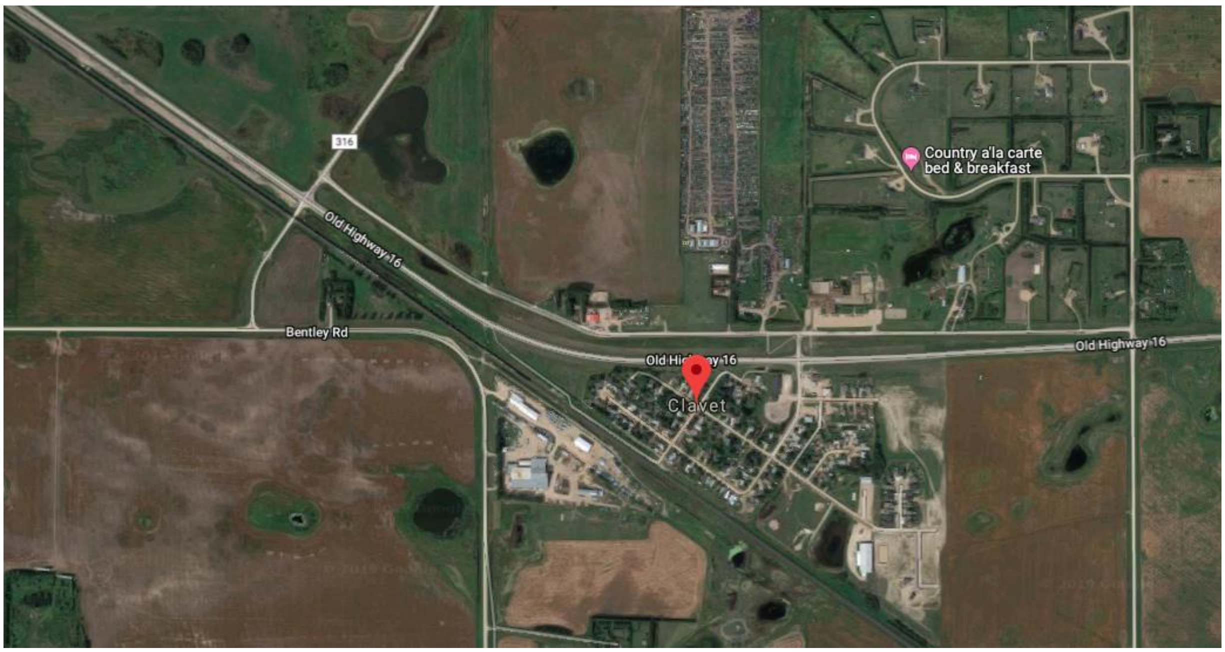
1. Introduction

1.1 Objectives:

The purpose of the project is to design an electrical distribution system for a food processing and production facility for a local business owner. This facility is in rural Saskatchewan, it will provide occupancy for office, industrial and a remote outbuilding for processes to be used in the facility.

Parameters:

Location: Clavet, SK



Main building (headquarters and plant):

Type of occupancy	Space (m^2)	Watts per square meter (W/m^2)	Area load (kW)	Number of panels	Area load per panel (kW)
Office	2000	50	100	6	16.7
Plant	20000	25	500	8	62.5

Outbuilding (1.5 km from plant):

Type of occupancy	Space (m^2)	Watts per square meter (W/m^2)	Area load (kW)	Number of panels	Area load per panel (kW)
Industrial	100	25	2.5		

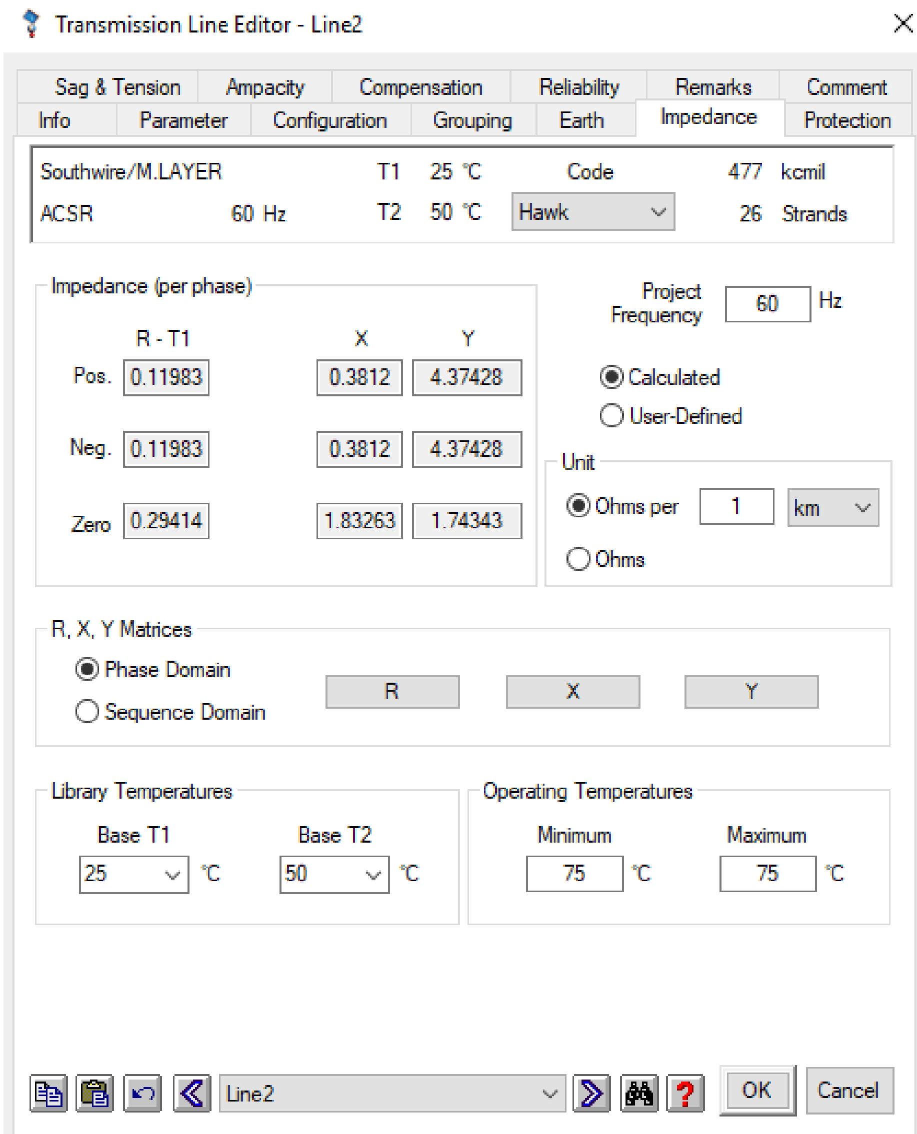
Total area load: (100 + 500 + 2.5) kW = 602.5 kW

1.2 Requirements:

- Verification of Transmission Line (ETAP model with some verification via hand calculations).
- General description of the Electrical Distribution System and its requirements.

- Information of the distribution components selected that meet the design requirements – busses, transformers, generator, etc. Wherever possible, examples of equipment that meet your minimum specifications should be provided.
- Verification of Voltage Regulation in the system (ETAP model with some verification via hand calculations). *Note: This is to be done at various loading for the system – 100% load, 75% load, 20% load.*
- Renewable Energy discussion and recommendations as well as an overview of proposed system.
- AutoCAD - Single Line Drawing.
- ETAP Model – Single Line.

2. Transmission Line



D = GMD = (AB * BC * CA)$^{1/3}$ = (3.61 * 3.61 * 7.22)$^{1/3}$ = 4.548 ft

D = 0.858 in; therefore r = 0.429 in = 0.0358 ft

$z = r_{AC} + j0.0029 * f * \log_{10}(D / r)$

$r_{AC} = (0.0436\ \Omega / 1000\ ft) * (3.28084\ ft / 1\ m) = 0.00014\ \Omega / m$

$x = [0.0029 * 60 * \log_{10}(4.548 / 0.0358)] = 0.37\ \Omega / 1000\ m$

$z = (0.00014 + j0.37\ \Omega / 1000\ m)$

$Z = (0.00014\ \Omega / m + j0.37\ \Omega / 1000\ m) * 25000\ m = 3.5 + j9.3\ \Omega$

From ETAP: z = 0.00012 + j0.38; Z = 2.99566 + j9.52992 Ω

3. Distribution System Design

This consists of the selection and sizing of the following components: buses, transformers, conductors, overcurrent protection and generator. Each component must meet a specific requirement to avoid shortage/excess power and prevent electrical hazards. The choice of electrical switches for over-current protection will be breakers. I am choosing breakers over fuses because even though both protect electric circuits from damages caused by excess current, fuses only operate once and must be replaced while breakers can easily be reset back to normal operations.

3.1 Full load current

Full load current for induction motors with voltages lesser or equal to 2300 V are provided in Table 44 of the Canadian Electrical Code book.

3.1.1 For motors with voltages greater the 2300 V, the full load current can be achieved using the following equations:

$I_{NOM} = P / (\sqrt{3} * V)$

$I_{FLA} = I_{NOM} / (p.f.)\ (eff.)$

The power factor and efficiency for this design we assume to be 0.9 and 0.9, respectively, and the following equations will be used to determine component selection and sizing.

e.g. CH-1: 1500 kW, 4160 V

$I_{NOM} = 1500\ kW / (\sqrt{3} * 4160\ V) = 208.2\ A$

$I_{FLA} = 208.2\ A / (0.9)\ (0.9) = 257\ A$

Motor	CH-1	CH-2	CH-3	LP-1
Bus	4	1	4	4
I_{FLA} (A)	257	257	85.7	31.9

3.1.2 For panel boards*,* the full load current can be achieved using the following equation:

$I_{FLA} = P / (\sqrt{3} * V * p.f)$

e.g. ELP-1 (Office): 16.7 kW, 600 V

I_{FLA} = 16.7 kW / (√3 * 600 V * 0.9) = 17.8 A

Panel boards connected directly to buses

Panel	LP-1	LP-2	LP-3	LP-4	ELP-1	ELP-2
Bus	2	2	3	3	5	5
I_{FLA} (A)	17.8	17.8	66.8	66.8	17.8	66.8

Panel boards connected via transformers (secondary)

Panel	PP-1	PP-2	PP-3	PP-4	PP-5	EPP-1	EPP-2	EPP-3
Bus	2	2	3	3	3	5	5	5
Voltage (V)	208	208	208	208	208	208	208	208
I_{FLA} (A)	51.4	51.4	192.8	192.8	192.8	51.4	192.8	192.8

3.1.3 For transformers *being fed via a bus,* the full load current (primary) can be achieved using the following equation:

I_{FLA} = S / (√3 * V)

e.g. transformer feeding Bus 5 from Bus 4

Rating: 1000 KVA, 4160/600 V

$I_{FLA\ (primary)}$ = 1000 kVA / (√3 * 4160) = 138.8 A

Panel	PP-1	PP-2	PP-3	PP-4	PP-5	EPP-1	EPP-2	EPP-3
Bus	2	2	3	3	3	5	5	5
Voltage (V)	600	600	600	600	600	600	600	600
I_{FLA} (A)	51.4	51.4	192.8	192.8	192.8	28.9	72.2	72.2

Transformer	$Bus_{2\text{->}1}$	$Bus_{3\text{->}1}$	$Bus_{7\text{->}1}$	$Bus_{8\text{->}1}$	$Bus_{5\text{->}4}$	$Bus_{6\text{->}4}$	$Bus_{9\text{->}4}$
Voltage (V)	4160	4160	4160	4160	4160	4160	4160
I_{FLA} (A)	31.2	104.1	138.8	31.2	138.8	208.2	69.4

For transformers feeding a bus, the full load current (secondary) can be achieved summing up the I_{FLA} of each component connected to the bus.

Transformer	$Bus_{2\text{->}1}$	$Bus_{3\text{->}1}$	$Bus_{7\text{->}1}$	$Bus_{8\text{->}1}$	$Bus_{5\text{->}4}$	$Bus_{6\text{->}4}$	$Bus_{9\text{->}4}$
Voltage (V)	600	600	600	600	600	600	600
I_{FLA} (A)	186.8	700.4	912	200.2	138.8	208.2	69.4

3.2 Over-current maximum protection

As mentioned earlier, circuit breakers will be the choice of electrical switch for over-current maximum protection.

For induction motors, circuit breaker current is provided in Table D16 of the Canadian Electrical Code book.

For panel boards and other loads, the circuit breaker current can be achieved using the following equations:

Breaker I = I_{FLA} * 3; (300% for voltages greater than 750 V)

Breaker I = I_{FLA} * 1.5; (150% for voltages lesser than 750 V)

e.g. ELP-1, I_{FLA} = 17.8 A

Over-current max = 17.8 A * 1.5 = 26.7 A

Real-world over-current maximum = 30 A

3.3 Conductor selection, sizing and minimum ampacity

For conductor sizing, the minimum conductor ampacity must be known to be able to determine the conductor size (kcmil/AWG). The minimum conductor ampacity can be achieved using the following equation:

Minimum conductor ampacity = I_{FLA} * 1.25

I will be using three copper conductors, rated no more than 5000 V and unshielded, in cable. Conductor sizes are provided in Table 2 of the Canadian Electrical Code book and my allowable ampacity is based on an ambient temperature of 90 deg C. Copper is a cheaper conductor when compared among other conductors with equal or higher conductivity. Aluminum might be cheaper and easier to install due to its lighter weight, but it has a higher risk of causing fires if not installed properly. Also, copper is low maintenance and more durable unlike aluminum which have a higher wear and tear rate, therefore, requiring more maintenance.

e.g. ELP-1, I_{FLA} = 17.8 A

Minimum conductor ampacity = 17.8 * 1.25 = 22.3 A

In table 2, 22.3 A, 14 AWG has an allowable ampacity of 25 A, therefore, this is an appropriate conductor size for ELP-1.

Bus 1

Component	Over-current max. (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A)	Conductor size (AWG)
CH-2	771	800	321.3	350

Bus 2

Component	Over-current max. (A) Sec/Pri	Real-world over-current max. (A) Sec/Pri	Minimum conductor ampacity (A) Sec/Pri	Conductor size (AWG) Sec/Pri
LP-1	26.7	30	22.3	14§
LP-2	26.7	30	22.3	14§

PP-1	77.1/43.3	80/45	64.3/36.1	6/10
PP-2	77.1/43.3	80/45	64.3/36.1	6/10

Bus 3

Component	Over-current max. (A) Sec/Pri	Real-world over-current max. (A) Sec/Pri	Minimum conductor ampacity (A) Sec/Pri	Conductor size (AWG) Sec/Pri
LP-3	100.2	110	83.5	4
LP-4	100.2	110	83.5	4
PP-3	289.1/108.3	300/110	240.9/90.3	0000/4
PP-4	289.1/108.3	300/110	240.9/90.3	0000/4
PP-5	289.1/108.3	300/110	240.9/90.3	0000/4

Bus 4

Component	Over-current max. (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A)	Conductor size (AWG)
CH-1	771	800	321.3	350
CH-3	257.1	300	107.1	3
FP-1	95.7	100	39.9	10

Bus 5

Component	Over-current max. (A) Sec/Pri	Real-world over-current max. (A) Sec/Pri	Minimum conductor ampacity (A) Sec/Pri	Conductor size (AWG) Sec/Pri
ELP-1	26.7	30	22.3	14§
ELP-2	100.2	110	83.5	4
EPP-1	77.1/43.3	80/45	64.3	6
EPP-2	289.1/108.3	300/110	240.9/90.2	0000
EPP-3	289.1/108.3	300/110	240.9/90.2	0000
Data Centre	462.6/162.4	500/175	385.5/135.4	500
Plant Control System	115.7/43.3	125/45	96.4/36.1	3/1

Bus 6

Component	Full load current (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A)	Conductor size (AWG)
P-1	22	40	27.5	12§
P-4	52	100	65	6
P-7	77	150	97.5	3
EX-1	32	60	40	10§
SF-1	77	150	97.5	3
RF-1	52	100	65	6

AC-1	144	250	181.3	00
BLR-1	99	200	125	2
BLR-2	99	200	125	2
CVYR-1	17	30	21.3	14§
CVYR-2	17	30	21.3	14§

Bus 7

Component	Full load current (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A)	Conductor size (AWG)
P-2	22	40	27.5	12§
P-5	52	100	65	6
P-8	77	150	97.5	3
EX-2	32	60	40	10§
SF-2	77	150	97.5	3
RF-2	52	100	65	6
AC-2	144	250	181.3	00

Bus 8

Component	Full load current (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A	Conductor size (AWG)
P-3	6.1	15	8.75	14§
P-6	17	30	21.3	14§
P-9	17	30	21.3	14§
EX-3	11	20	13.75	14§
SF-3	27	50	35	10§
RF-3	22	40	27.5	12§

Bus 9

Component	Full Load Current (A)	Real-world over-current max. (A)	Minimum conductor ampacity (A)	Conductor size (AWG)
P-10	99	200	125	2
P-11	99	200	125	2

3.4 Transformer selection and sizing

This facility consists of equipment with different voltage ratings; therefore, transformers are required. A major advantage of a transformer is its ability to transform voltages and currents without changes in the apparent power, this produces higher efficiency rate, lower voltage regulation and power losses.

This facility will mostly consist of Δ-Δ connected transformers because unlike Δ-Δ connected transformers, there exist an imbalance in voltages if Y-Y transformers are properly grounded.

Transformer sizing on a three-phase system, can be achieved using the following equations:

$S = \sqrt{3} * V * I_{FLA}$

e.g. EPP-1 (Office): 16.7 kW, 208 V

I_{FLA} = 51.4 A

S = √3 * 208 * 192.8 = 69.5 kVA

A 69.5 kVA, 600/208 V transformer is not available, therefore, we use an available transformer (real-world) having a size greater than and nearest to 69.5 kVA.

Therefore, real-world transformer size = 75 kVA, 600/208 V

Transformer	Power (kVA)	Voltage (V) Sec/Pri	Over-current Max (A) Sec/Pri	Real-world over-current Max (A) Sec/Pri	Minimum conductor A Sec/Pri	Conductor size (AWG) Sec/Pri
Bus_2 to Bus_1	225	600/4160	280.2/93.7	300/100	233.3/39	0000/10
Bus_3 to Bus_1	750	600/4160	1050.6/312.3	1200/350	875.5/130.1	2x 600/1
Bus_7 to Bus_1	1000	600/4160	1368/416.4	1600/500	1140/173.5	2x 900/00
Bus_8 to Bus_1	225	600/4160	300.3/93.7	350/100	250.3/39	0000/10
Bus_5 to Bus_4	1000	600/4160	1185.8/416.4	1200/500	988.1/281.3	2x 700/250
Bus_6 to Bus_4	1500	600/4160	1716/624.5	2000/700	1430/260.3	2x 1750/250
Bus_9 to Bus_4	500	600/4160	594/208.2	600/225	495/86.8	700/4

3.5 Bus sizing

Buses are a more flexible and efficient system in power distribution. It cost less and it's easy to install. Keeping in mind that in the future, more equipment could be installed in this facility, therefore, it is a good practice installing busways directly feeding panel boards and motors with a doubled ampere rating.

Bus sizing can be achieved by simply summing up the full load current of equipment being fed from the bus, while considering the respective duty cycles of these equipment.

e.g. P-1: I_{FLA} = 22 A, 50% duty cycle; CVYR-1 and CVYR-2: I_{FLA} = 17 A, 50% duty; all being fed from Bus 6.

Bus size = 22 A + 17 A = 37 A (select an available bus size greater and nearest to value)

Considering future installation;

Bus size = 37 A * 2 = 74 A (select an available bus size greater and nearest to value)

Bus	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9
Bus amp rating (A)	1353.3	186.8	700.4	791	790.2	1144	912	200.2	396
Real-world bus amp rating (A)	1600	225	800	800	800	1200	1000	225	400
Over-current max. (A)	4059.9	280.2	1050.6	2373	1185.3	1716	1368	300.3	594

Real-world over-current max. (A)	5000	400	1200	2500	1200	2000	1600	400	600
Minimum conductor amp (A)	1691.6	233.5	875.5	988.8	987.8	1430	1140	250.3	495
Total real power (kW)	8366.4	87.4	327.5	4886.4	369.5	421.3	335.6	67.1	149.1
Total apparent power (kVA)	9262	97.1	363.9	5429.3	410.6	468.1	372.9	74.6	165.7

3.6 Generator sizing

A generator is to be connected via a transfer switch to a bus that feeds the essentials loads. Bus 4 has a total power of 4886.4 kW, therefore, the dual fuel generator with a 60 Hz, 5600 kWe rating, 514 rpm manufactured by CAT is the preferred choice to be installed in this facility.

KWe*			Generator Set Model**	Configuration
Standby	Prime	Contin.		
500 rpm				
5600	5290	5290	6CM46DF	World Bank Certification (Stage I and II)
6600	6170	6170	7CM46DF	World Bank Certification (Stage I and II)
7500	7050	7050	8CM46DF	World Bank Certification (Stage I and II)
8500	7930	7930	9CM46DF	World Bank Certification (Stage I and II)
11300	10580	10580	12CM46DF	World Bank Certification (Stage I and II)
15100	14110	14110	16CM46DF	World Bank Certification (Stage I and II)

3.7 Power factor correction

The 25 km transmission line has a reactive impedance of 9.52992. To correct the phase shift in this system, the system needs to have a unity power factor which we can achieve by doing the following:

e.g. Lump 2: S = 363.9 kVA, P = 327.5 kW

$Q = \sqrt{(S^2 - P^2)} = \sqrt{(363.9^2 - 327.5^2)} = 158.641$ kvar

$Q = (3 * V^2) / X$

Therefore, $X = (3 * V^2) / Q = (3 * 600^2)$ V / 158641) = 6.8078 Ω

$X_C = 1 / (2 * pi * f * C)$

Therefore, $C = 1 / (2 * pi * f * X_C) = 1 / (2 * pi * 60 * 6.8078) = 0.0003896$ F = 389.6 μF

4. Load Profile

The power required to be supplied to this facility is the summation of the area load and total facility power, which is:

8366.4 kW + 602.5 kW = 8968.9 kW

To determine to amount of energy to be supplied annually, we therefore, implement the following steps:

Weekend (15%)

8968.9 kW * 0.15 * 24 hr. = 32288 kWh

Weekdays

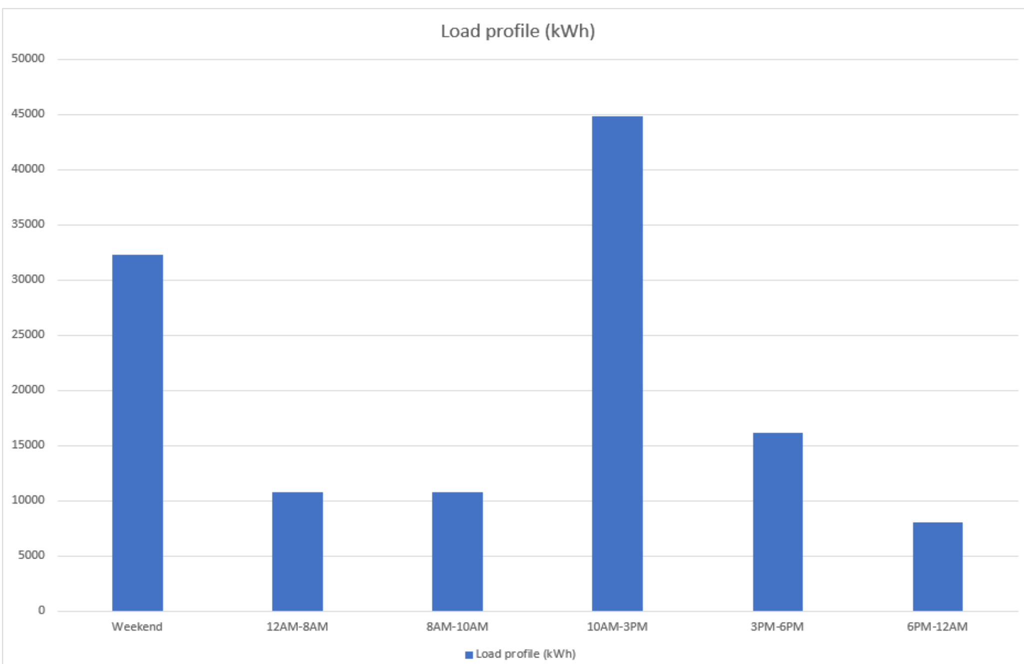
12 AM – 8 AM (15%) = 8968.9 kW * 0.15 * 8 hr. = 10762.7 kWh

8 AM – 10 AM (60%) = 8968.9 kW * 0.6 * 2 hr. = 10762.7 kWh

10 AM – 3 PM (100%) = 8968.9 kW * 1.0 * 5 hr. = 44844.5 kWh

3 PM – 6 PM (60%) = 8968.9 kW * 0.6 * 3 hr. = 16144 kWh

6PM – 12 AM (15%) = 8968.9 kW * 0.15 * 6 hr. = 8072 kWh



Total power per week

(32288 kWh * 2 days) + [(10762.7 + 10762.7 + 44844.5 + 16144 + 8072) kWh * 5 days]

= 517505.5 kWh / week

Annual Energy

(517505.5 kWh / week) * (52 weeks / year) = 26910286 kWh / year = 26910.3 MWh / year

5. Renewable Energy

Annual renewable energy to be supplied to this facility is required to be 10% of the annual energy, therefore:

(26910.3 MWh / year) * 0.1

= 2691.0 MWh / year

Renewable energy is a clean and environmental-friendly source of energy. Energy sources include wind, solar, hydro and biomass. It has lower maintenance requirements, saves money on the long run and has its environmental and health benefits such as little to no pollution.

5.1 Wind Energy

The table below contains the annual mean wind speed and energy for Clavet, SK. This data is obtained from the Canadian Wind Energy Atlas.

Values | Roses | Histograms | Turbine formula

Numerical Values at 50m

Latitude = 52.013, longitude = -106.349

Period	Mean Wind Speed	Mean Wind Energy	Weibull shape parameter (k)	Weibull scale parameter (A)
Annual	6.13 m/s	205.38 W/m2	2.15	6.92 m/s
Winter (DJF)	6.74 m/s	254.75 W/m2	2.33	7.61 m/s
Spring (MAM)	5.71 m/s	160.50 W/m2	2.23	6.44 m/s
Summer (JJA)	5.44 m/s	146.69 W/m2	2.09	6.14 m/s
Fall (SON)	6.50 m/s	233.88 W/m2	2.26	7.34 m/s

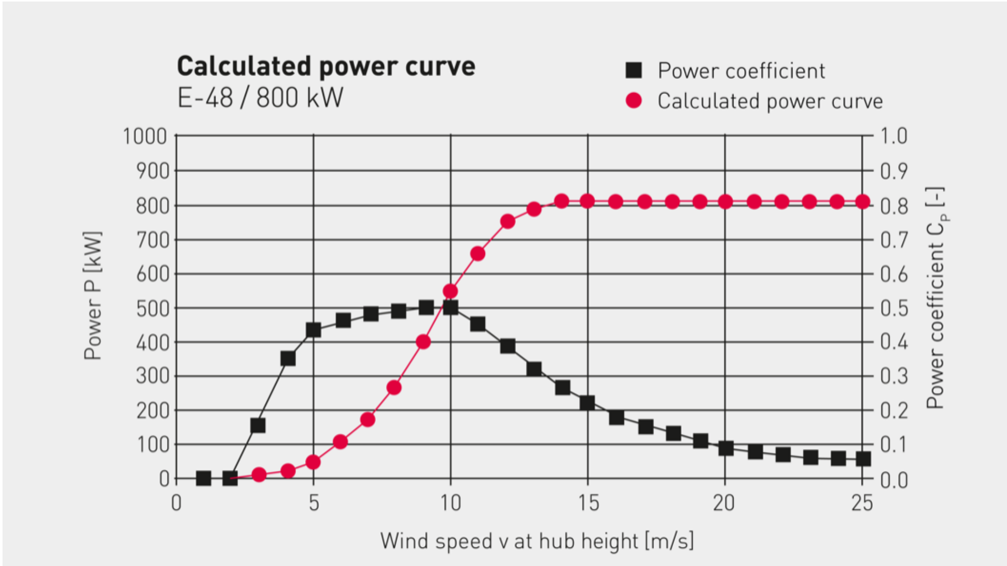
My choice of wind turbine to generate renewable energy are E-48 and E-53 by Enercon. They both have a rated power of 800 kW and a three-blade rotor with a diameter of 48 m and 52.9 m, respectively. The annual renewable energy generated by the wind turbine can be achieved using the following equation:

$P_{mechanical} = 0.5 * C_p * P * A * V^3$

Annual wind speed = 6.13 m/s

Rotor diameter = 48 m

Rotor radius = (48 / 2) = 24 m



$P_{mechanical}$ = 0.5 * 0.45 * 1.013 kg/m^3 * pi * (24 m)^2 * (6.13 m/s)^3 = 95005 kW

Annual renewable energy = 95005 kW * 24 hr. * 365 days = 832.2 MWh / year

A combination of three wind turbines consisting of two E-48 wind turbines and one E-53 wind turbine will be installed in this facility, further doubling the annual renewal wind energy generated, therefore;

Annual renewable energy = 832.2 MWh / year * 3 = 2496.7 MWh / year

(2496.7 / 26910.3) * 100 = 9.3%

Therefore, the wind turbine system will generate 9.3% of the annual energy.

5.2 Solar Energy

My choice of solar panel to generate renewable energy is NeON R by LG. It is a 1700 mm x 1016 mm and a 6 x 10 monocrystalline N-type solar panel which has a high-power output of 365 W. The annual renewable energy generated by the wind turbine can be achieved as follows:

Total renewable energy to be generated = 2691 MWh / year

Total renewable energy to generated by wind = 2496.7 MWh / year

Renewable energy to be generated by solar = 2691 – 2496.7 = 194.3 MWh / year

Therefore, 19430000 / (24 hr * 365 days) = 22260.3 W

Number of panels = 22260.3 W / 365 W = 61 panels.

Area of panel = 1.7 m * 1.016 m = 1.7272 m^2

Total solar system area = 1.7272 * 61 = 105.4 m^2

6. ETAP Model

<u>Hand calculation</u>

ETAP provides the impedances for each transformer using the per unit system, we can determine the actual shunt and series impedance by finding the base impedance and multiplying it by the per unit value. We determine the base impedance as follows:

$Z_{base} = \sqrt{3} * V^2_{base} / S_{base}$

T_3 has a transformer rating of 750 kVA, 4160 / 600 V which feeds a 327.5 kW load having 0.9 lagging power factor. T_1 has a transformer rating of 10 MVA, 25000 / 4160 V which is connected via Bus 1 to cable 42 and T_3.

<u>For T_3</u>

$Z_{base,T3} = \sqrt{3} * 4160^2 / 750000 = 39.996\ \Omega$

$\%R = 1.408 = 0.01408$ pu

$\%X = 5.575 = 0.05575$ pu

$\mathbf{Zse_{PU}} = R_{PU} + jX_P = 0.01408 + j0.05575$ pu

Therefore, series impedance:

$\mathbf{Zse_{T3,P}} = \mathbf{Zse_{PU}} * Z_{base} = (0.01408 + j0.05575) * 39.996\ \Omega = 0.563 + j2.23$

$\%G = 0.125 = 0.00125$ pu

$\%B = 0.484 = 0.00484$ pu

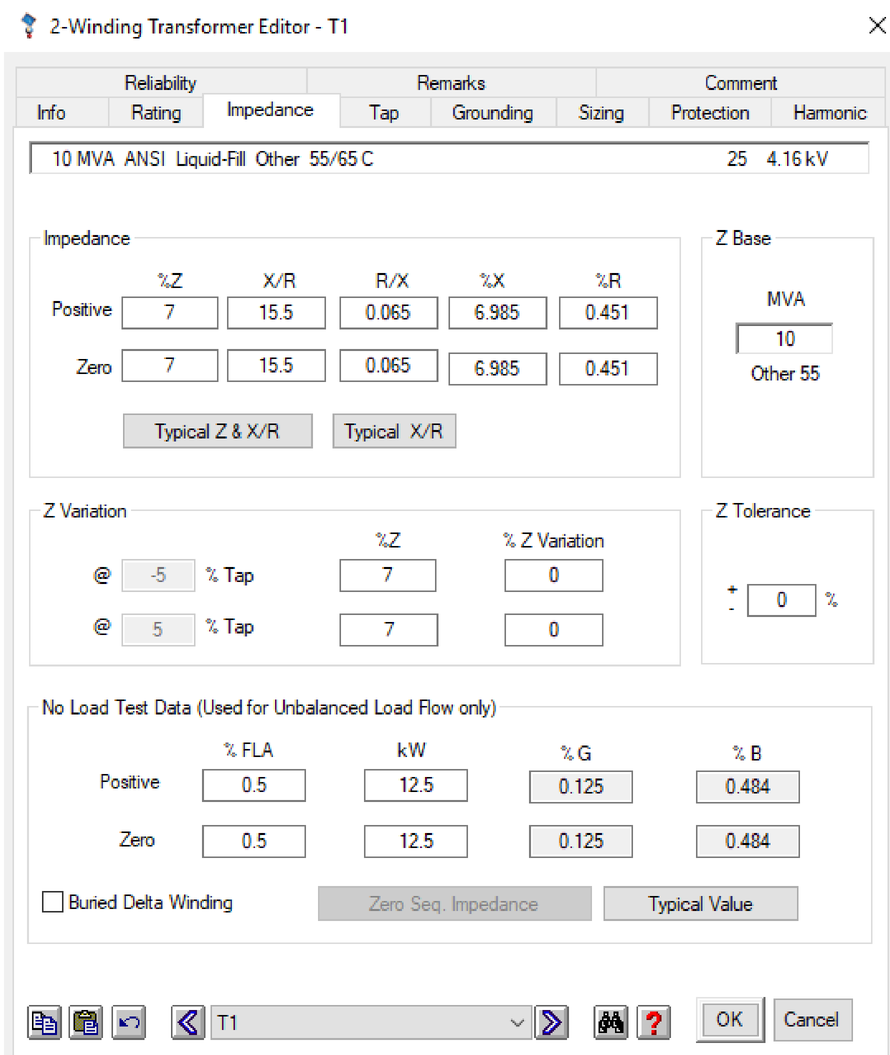
$\mathbf{Ye_{PU}} = G_{PU} + jB_{PU} = 0.00125 - j0.00484$ pu

$\mathbf{Zsh_{PU}} = (1 / G_{PU}) + (jB_{PU}) = Rc_{PU} + jXm_{PU} = 800 + 206.6$ pu

Therefore, shunt impedance:

$\mathbf{Zsh_{T3,P\ (shunt)}} = \mathbf{Zsh_{PU}} * Z_{base} = (800 + j206.6) * 39.996\ \Omega = 31997 + j\ j8264\ \Omega$

For T_1



$Z_{base,T1}$ = √3 *25000^2 / 10000000 = 108.3 Ω

%R = 0.451 = 0.00451 pu

%X = 6.985 = 0.06985 pu

$\mathbf{Z_{PU}} = R_{PU} + jX_P$ = 0.00451 + j0.06985 pu

$\mathbf{Zse_{T1,P}} = \mathbf{Zse_{PU}} * Z_{base}$ = (0.00451 + j0.06985) * 108.3 Ω = 0.488 + j7.561 Ω

The equivalent series and shunt impedance in the high voltage or primary side of T_3 are 0.563 + j2.23 and for T_1 is 0.488 + j7.561 Ω. With the load power and power factor known, we can find current and its phase angle using the following equations:

P = √3 * V * I * p.f.

Therefore, I = P / (√3 * V * p.f.)

P = 327.5 kW, p.f. = 0.9 lagging

I = P / (√3 * 600 * 0.9) = 350.2 A

$\cos^{-1}(0.9) = -25.84$

$\mathbf{I_{T3,S}}$ = 315.2 - j152.64 A

The current in the low voltage or secondary side of T_3 is 315.2 - j152.64 A. We must refer this current to the high voltage or primary side of T_3 which can be achieved by doing the following.

a = 4160 / 600 = 6.93

$\mathbf{I_{T3,S}}$ / a = (315.2 - j152.64 A) / 6.93 = 45.46 - j22 A

<u>Note</u>

$_{\mathbf{PU}}$ represents per unit

se represents series

sh represents shunt

$_{\mathbf{T3,P}}$ represents transformer 3, primary side

$_{\mathbf{T3,S}}$ represents transformer 3, secondary side

$_{\mathbf{T1,P}}$ represents transformer 1, primary side

<u>*For Cable$_{42}$*</u>

$\mathbf{Z_{cable}}$ is the impedance in cable$_{42}$

$\mathbf{Z}_{X,S} = \mathbf{Z}_{T3,P} + \mathbf{Z}_{cable} = (0.563 + j2.23) + (0.184 + j0.035) = 0.747 + j2.265\ \Omega$

$\mathbf{Z}_{X,S}$ is the equivalent impedance in the low voltage or secondary side of T_1. Also, the current flowing through the high voltage or primary side of T_3 is equal to the combination of the current flowing through the shunt and series impedance of low voltage or secondary side of T_1, therefore, we have:

$\mathbf{V}_{T3,P} = a * \mathbf{V}_{T3,S} + \mathbf{I}_{T3,S} / a * \mathbf{Z}_{X,S} = (4160 + j0) + (45.46 - j22)\ (0.747 + j2.265) = 4243.8 + j86.5$ V

$\mathbf{I}_{T3,P} = \mathbf{I}_{EX3,P} + \mathbf{I}_{T3,S} / a = \mathbf{V}_{P3} / R_C + \mathbf{V}_{P3} / jX_M + \mathbf{I}_{T3,S} / a$

$\mathbf{I}_{T3,P}$ =[(4243.8 - j86.5) / 31997] + [(4243.8 - j86.5) / j8264] + (45.46 - j22) = 45.6 - j22.51 A

To determine the primary voltage of T_1, we must refer $\mathbf{I}_{T3,P}$ and $\mathbf{Z}_{X,S}$ to the high voltage or primary side f T_1. Therefore, we have:

$a = (25000 / 4160) = 6.01$

$\mathbf{Z_{X,P}} = a^2 * \mathbf{Z_{X,S}} = (6.01)^2 * (0.747 + j2.265) = 26.98 + j\,81.8\ \Omega$

$\mathbf{I_{T1,P}} = \mathbf{I_{T3,P}} / a = (45.6 - j22.51) / 6.01 = 7.589 - j3.746$ A

We can do the following to determine the primary voltage in T_1 and the total equivalent impedance from Bus 1 to Bus 3 (impedance in the T_1, T_3 and cable):

$\mathbf{Z_{Y,P}} = \mathbf{Z_{X,P}} + \mathbf{Z_{T1,P}} = (26.98 + j\,81.8) + (0.488 + j7.561) = 27.47 + j89.36\ \Omega$

$\mathbf{V_{T1,P}} = a * \mathbf{V_{T3,P}} + \mathbf{I_{T1,P}} * \mathbf{Z_{Y,P}}$

$\mathbf{V_{T1,P}} = (6.01)\,(4243.8 + j86.5) + (7.589 - j3.746)\,(27.47 + j89.36) = 26046.8 + j1095.1$ V

$\mathbf{V_P} = 26069.8\, e^{j2.4}$ V

Voltage Regulation = $(V_P - a * V_S) / V_S$ = [(26069 – 25000) / 25000] * 100% = 4.2%

From ETAP, voltage regulation for 100% load

Voltage Regulation = 91.76 - 87.89 = 3.9%

Comparing both voltage regulations from the hand calculation and ETAP, they are 4.2% and 3.9%, both being approximated to a value of 4%, the 0.3% difference is as a result of rounded off figures done in calculation.

7. Recommendations and conclusion

After a careful analysis of multiple factors which are conductor type and size, ampacity, configuration, voltage regulation. I suggest the power distribution system has the following parameters:

Conductor Type	Southwire M Layer - Hawk
Length	25 km
Span	3.61 ft
Height	25 ft
Physical configuration	Horizontal
Conductor configuration	Three phase

References

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