Rebel Foods
Load Balancing in Three Phase Circuits

Aditya Harakare
Electrical Engineering Intern
Mentored by: Sudeshna Trilok

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Contents

1 AIM

The primary aim of the project was:

- To understand three phase electrical power.
- Understand Load Balancing and Load Scheduling Techniques.
- Analysing how these techniques can be applied to make the typical Rebel Kitchen more energy efficient.
- Building an interactive calculator that takes inputs of equipment specifications and outputs load balancing schema.

2 Three Phase Electrical Power

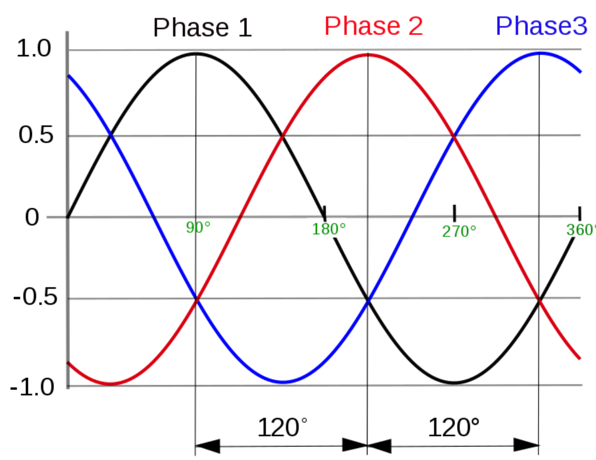

Figure 1: Voltage Waveforms
By User:J JMesserly modification of original svg by User:SiriusA - File:3-fas-spänningar.svg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5607023

2.1 What is Three Phase Power?

- Three-phase electric power is a common method of alternating current electric power generation, transmission, and distribution.

- It is used to power large motors and other heavy loads.

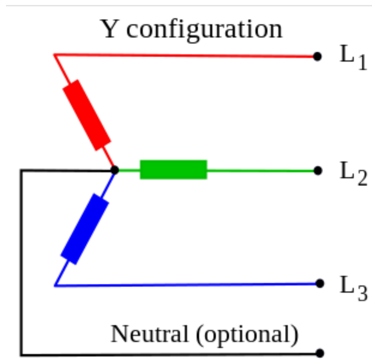

Figure 2: Star Load Configuration
By Svjo - Own work, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=24823731

2.2 Benefits of Three phase Power

- It is more economical than single phase power.
- Can transmit 3 times as much power using just 1.5 times as many wires. Thus, the ratio of capacity to conductor material is doubled.
- It ensures constant power transfer to a balanced linear load.

3 Balancing of Loads in the Power Lines

3.1 Connection of Loads across three phase supply

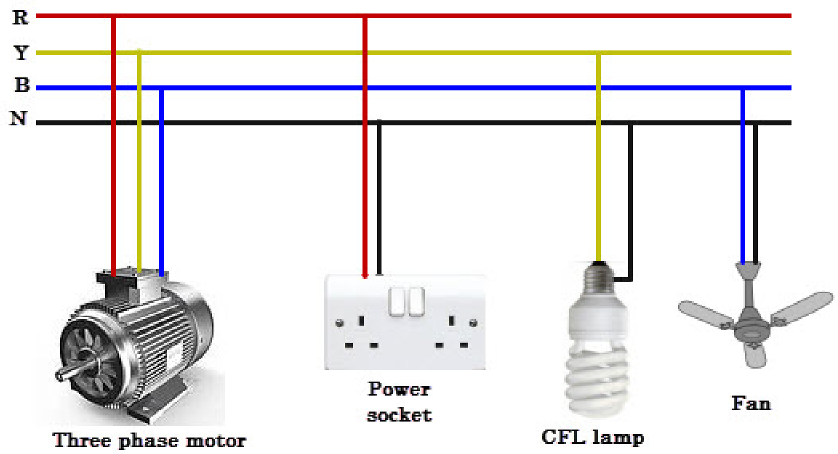

Figure 3: Connection of Different Loads on Three Phase Supply
electronics.stackexchange.com

- The Rebel Kitchen consists of three phase as well as single phase loads.
- Three phase loads are connected to all the three live phases of the supply and draw power from each of the supply lines equally.
- Single Phase Loads are connected between one live phase line of the three (R/Y/B) and the other end is connected to the neutral wire.
- The connections are explained in Figure: 3
- The single phase source voltage is assumed to be $220V(RMS)$ at 50Hz for all the calculations.

3.2 Need for Balancing of Loads

- To minimize the energy losses.
- The neutral current α eddy current losses in the upstream transformer.

- To ensure equal voltage magnitudes properly aligned phase angles at the loads in the three phases. Having unequal impedance implies that the current in each phase is different and hence there will be unequal voltage drops across the resistances in the power supply lines. This is further illustrated in the simulations. Refer Figure 6

4 MATLAB Simulations

4.1 Simulation Schematic

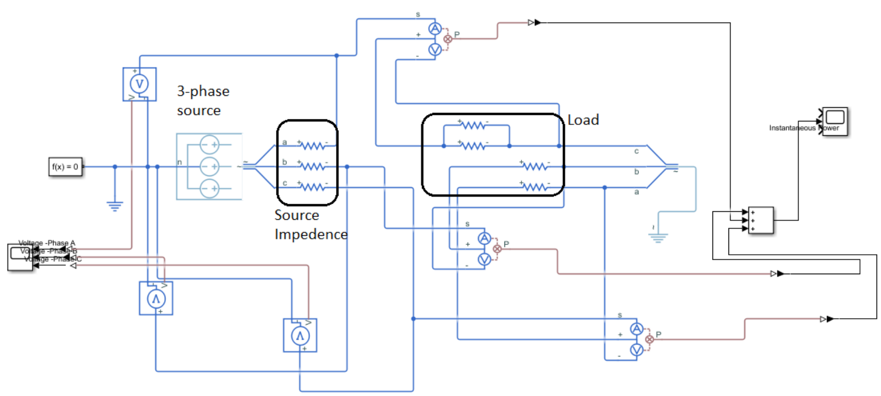

Figure 4: Schematic Used for Simulations

- The schematic used for simulations is illustrated in the Figure 4
- It consists of a 3-phase source, equal source resistances, resistive load, power measuring instruments, adder and oscilloscopes for viewing of the plots.

4.2 Balanced Load

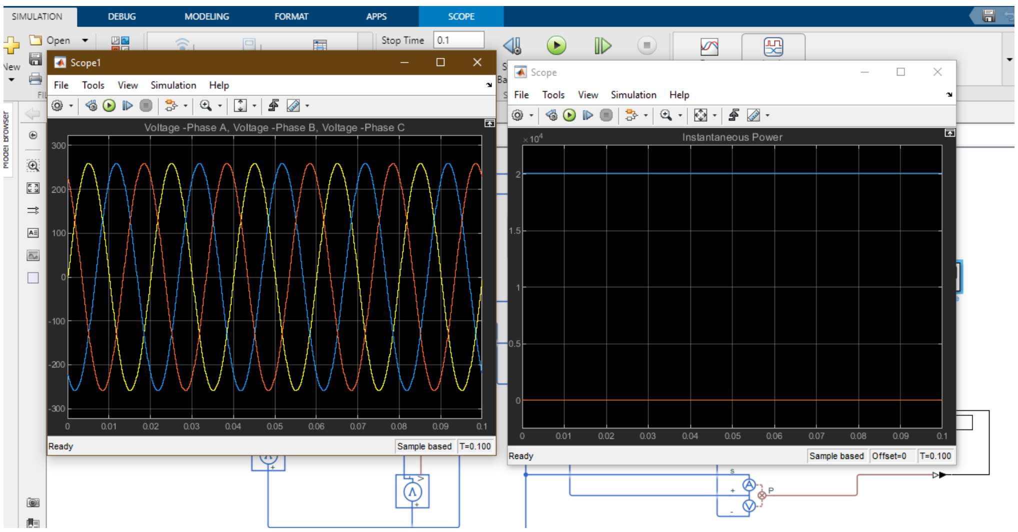

Figure 5: Waveforms generated for Balanced Load

- The waveform to the left of Figure 5 is of the voltages in the three phases across the loads.
- We can see that the magnitude of the voltages are equal in all the three phases and the waveforms are shifted by 120°each.
- To the right is the total power drawn by the 3 loads. We can see that this power drawn is a constant value. Hence, if the load is a three phase load, it draws constant instantaneous power unlike the single phase loads we use for domestic applications.
- Hence, 3 phase motors and other equipment are smooth in operation and have various advantages over single phase loads.

4.3 Unbalanced Load

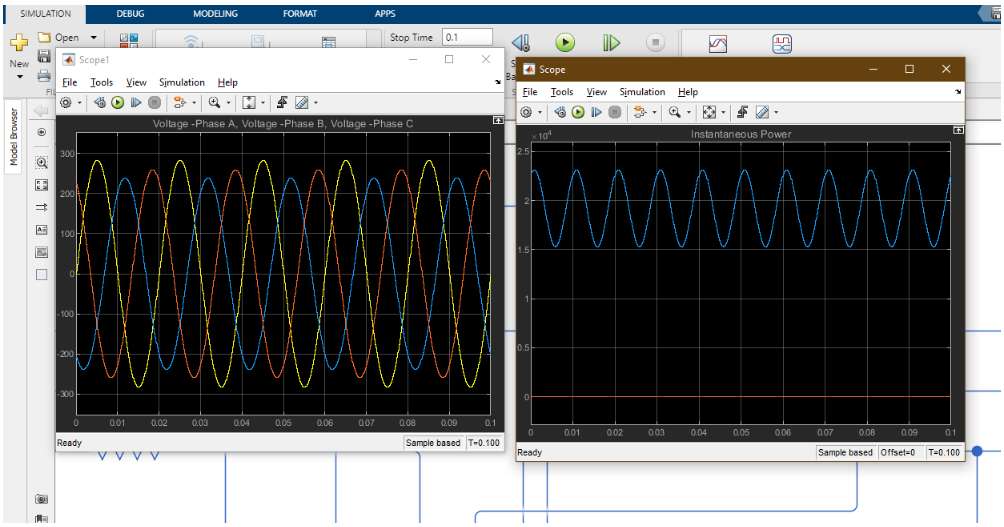

Figure 6: Waveforms generated for Unalanced Load

- The waveform to the left of Figure 5 is of the voltages in the three phases across the loads.
- We can see that the magnitude of the voltages are different in all the three phases.
- To the right is the total power drawn by the 3 loads. We can see that this power is no longer a constant value and oscillates with the voltage.

4.4 Conclusion

- Hence as we saw in the second case the voltages are not equal in magnitude. If an additional three phase load is connected across these lines in the second case, it would result in extensive heating and damage of the load.
- The difference in the voltage magnitude is magnified in the simulation for visual purposes. In reality, a difference of 2% or grater can harm a 3-phase induction motor.

- Hence it is extremely essential to balance the single phase loads across the three phases to the maximum extent possible.

5 Load Balancing Software for Resistive Loads

5.1 Problem Statement

- We are given a list of resistive single phase loads along with their specifications.
- The task was to divide these loads across three phases optimally and output the load balancing schema.

5.2 Algorithm

```
# Sort the array of single phase equipments in descending order
single_ph_array = sorted(single_ph_array, key=itemgetter(1), reverse=True)

# Assign each equipment of single phase array either to R/Y/B phase depending on the existing loads
# The equipment with highest power requirement gets assigned first
# The phase with the minimum load gets assigned the next equipment in the sorted array
for i in range(0, len(single_ph_array)):
    sum_r = sum(r_ph_power)         # Maintain Counter for current phase load
    sum_y = sum(y_ph_power)         # Maintain Counter for current phase load
    sum_b = sum(b_ph_power)         # Maintain Counter for current phase load
    if sum_r < sum_y:
        if sum_r < sum_b:
            r_array.append(single_ph_array[i])
            r_ph_power.append(single_ph_array[i][1])
        else:
            b_array.append(single_ph_array[i])
            b_ph_power.append(single_ph_array[i][1])
    elif (sum_y < sum_b):
        y_array.append(single_ph_array[i])
        y_ph_power.append(single_ph_array[i][1])
    else:
        b_array.append(single_ph_array[i])
        b_ph_power.append(single_ph_array[i][1])
```

Figure 7: Algorithm for Single Phase Resistive Loads

- We first sort the single phase resistive equipment in the descending order of their power requirements.
- We then maintain 3 variables which contain the current power drawn from the power lines.
- We allocate the next equipment to the phase which is drawing minimum amount of power and then update the 3 variables.
- We do this process until all the equipment are allocated a phase.
- The final allocation is the best possible schema for load balancing.

5.3 Version 1

- The first version of the software was simply designed to test the algorithm.
- It took the resistance value of the equipment list as input from the terminal and gave the load balancing schema as the output.

5.4 Version 2

- Since the resistance values are not directly available from the equipment specifications given, this software takes the power requirement of the equipment as the input.

- A screenshot explaining the working of the software is shown in Figure 8.

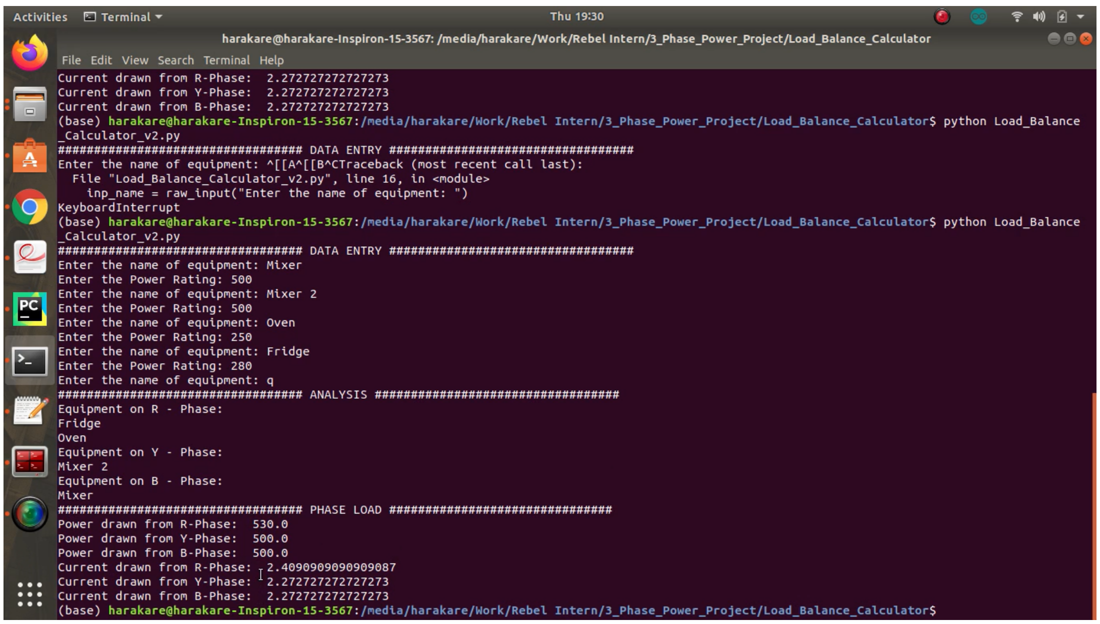

Figure 8: Version 2 Demonstration

5.5 Version 3

- The Rebel kitchen not only consists of single phase equipment but also has 3 phase loads.

- The Version 3 of the software also accepts one more argument along with the power rating which specifies the number of phases required.

- A screenshot explaining the working of the software is shown in Figure 9.

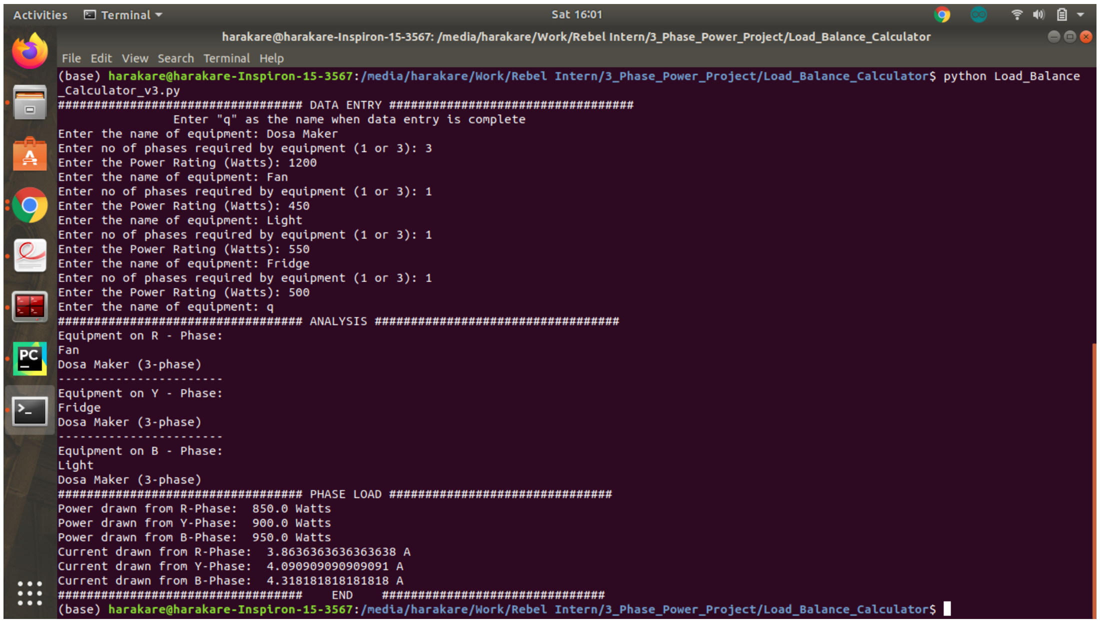

Figure 9: Version 3 Demonstration

5.6 Version 4

- This is the final version for load balancing of resistive equipments.
- This software takes the input from an excel file in the format shown in Figure 10.
- The output schema is displayed on the terminal as well as stored in a file named *'Load_Balance_Results.txt'*
- A sample output file is shown in Figure 11 and 12.

	A	B	C	D	E
1	**Machine/Fixture**	**Variable Name**	**Qty**	**Single/Three Phase**	**Power at Peak (kW)**
2	Auto Fryer		2	1	3
3	Combi Oven		1	3	15
4	Bain Marie		6	1	3
5	Microwave		4	1	1
6	Under Counter Chiller		2	1	1.5
7	Makeline		1	1	1.5
8	Impinger Oven-T98G		1	1	1
9	Proofer		1	1	1.8
10	Dosamatic		1	1	5
11	Idli Steamer		1	1	3
12	Mixer Grinder		1	1	0.75
13	Infra Red Routing Table		1	1	6
14	Vertical Chiller		1	1	1.5
15	Deep Freezer		2	1	1
16	Rice Cooker		1	1	2.5
17	Walk-In Cold Room		1	3	12
18	Computer		1	1	0.2
19	Display		4	1	0.1
20	Lights		1	1	0.4
21	UPS		1	1	1.5

Sheet1

Figure 10: Version 4 Input File

```
######################## Load Balance Results ####################
Equipment on R - Phase:
Auto Fryer
Auto Fryer_2
Bain Marie_3
Bain Marie_6
Proofer
Under Counter Chiller
Vertical Chiller
Microwave_2
Impinger Oven-T98G
Mixer Grinder
Combi Oven(3-phase)
Walk-In Cold Room(3-phase)
-----------------------
Equipment on Y - Phase:
Dosamatic
Bain Marie
Bain Marie_4
Idli Steamer
Under Counter Chiller_2
UPS
Microwave_4
```

Figure 11: Version 4 Output File (1)

```
-----------------------
Equipment on B - Phase:
Infra Red Routing Table
Bain Marie_2
Bain Marie_5
Rice Cooker
Makeline
Microwave
Microwave_3
Deep Freezer
Lights
Display_3
Combi Oven(3-phase)
Walk-In Cold Room(3-phase)
############################ PHASE LOAD #########################
Power drawn from R-Phase: 28550.0 Watts
Power drawn from Y-Phase: 28500.0 Watts
Power drawn from B-Phase: 28500.0 Watts
Current drawn from R-Phase: 129.77272727272728 A
Current drawn from Y-Phase: 129.54545454545453 A
Current drawn from B-Phase: 129.54545454545453 A
############################    END    ##########################
```

Figure 12: Version 4 Output File (2)

6 Load Balancing Software for a combination of Resistive and Reactive Loads

- Now each of our loads if either of the three types: Resistive, Inductive or Capacitive.
- Hence the impedance of each load is a complex value and we can't use the previous algorithm for load balancing.

6.1 Different Approaches

6.1.1 Minimize Difference in $|z|$?

- We can arrange all the elements in decreasing order of $1/|z|$ and continue with the same algorithm as used previously.
- In this way, we are actually minimizing the difference in the magnitude of line currents in the three phases.
- But since we have no information about the phase, this balancing can lead to large undesirable neutral current as shown in Figure 13.

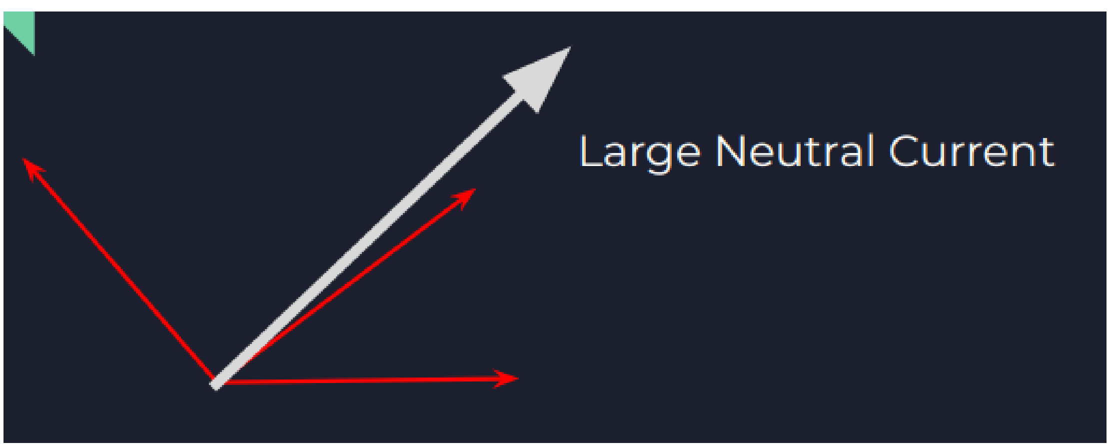

Figure 13: Current Phasors

6.1.2 Minimize the neutral current?

- Another approach might be to minimize the neutral current.
- The neutral current expression can be calculated by adding the three phase currents.

$$NeutralCurrent = V_o \times \left[\frac{1}{Z_1} - \frac{1}{2Z_2} - \frac{1}{2Z_3} + j\left(\frac{\sqrt{3}}{2Z_2} - \frac{\sqrt{3}}{2Z_3} \right) \right]$$

- However, since the currents in the 3 phases can be unequal and still add up to zero, this method also doesn't serve the complete purpose. This is illustrated in Figure 14.

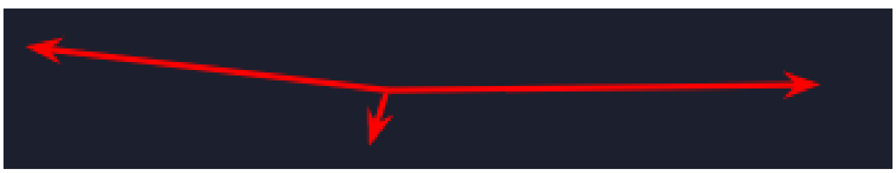

Figure 14: Current Phasors

6.1.3 The Best Approach

- We know that when $Z_1 = Z_2 = Z_3$, the circuit is completely balanced.
- Hence, let us define a cost function which quantifies the imbalance in the circuit and then we'll try to minimize this function. Hence, I defined a function:

$$f = |r_{imp} - y_{imp}| + |y_{imp} - b_{imp}| + |r_{imp} - b_{imp}| \tag{1}$$

  where x_{imp} is the current impedance on the $x - phase$.

- However, this algorithm is not scalable as it requires comparisions of order 3^N. (N is the number of loads)

6.2 Version 5

6.2.1 Logic Used:

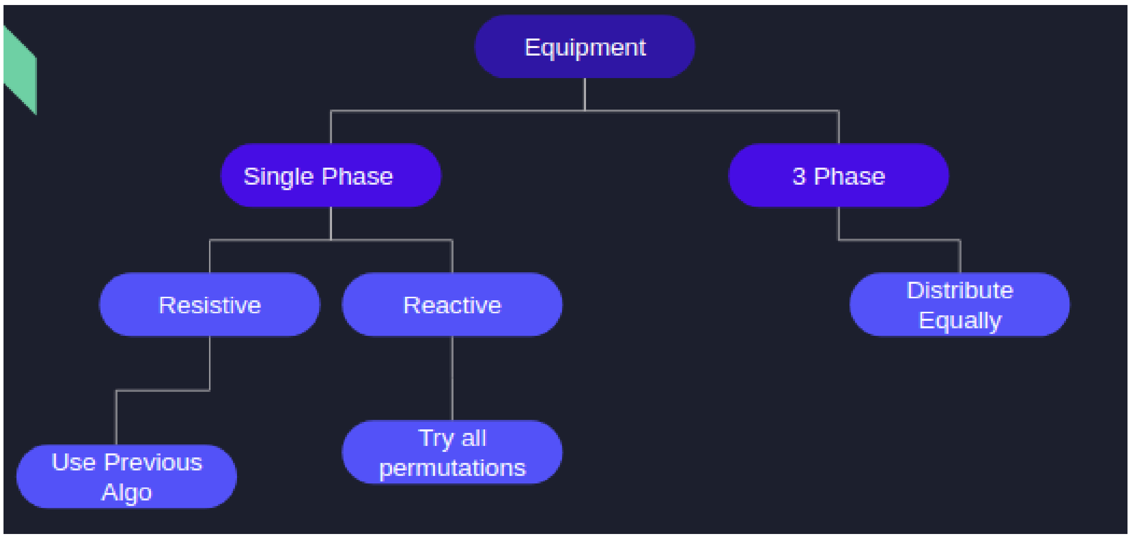

Figure 15: Splitting of data in Version 5

- Since, the algorithm described above is not scalable, we don't use it directly.
- We first split the given list of single phase equipment into resistive and reactive components as shown in Figure 15. Since the resistive and reactive components constitute two different dimensions, we can treat them separately.
- We then use the same algorithm as in Version 4 for resistive components.
- For the reactive components which have both positive and negative impedances, we try all the permutations and compute the cost according to equation 1.
- The permutation for which the cost is minimum is the best possible load balancing schema.
- The permutations are formed by counting the numbers of the base 3.

6.2.2 Working Demo

Machine/Fixture	Variable Name	Qty	Single/Three Phase	Power at Peak (kW)	Type of Load
A		3	1	10	Resistive
B		1	1	10	Inductive
C		1	1	10	Inductive
D		1	1	10	Capacitive
E		1	1	18	Inductive
F		2	3	10	Resistive

Figure 16: Version 5 - Input Format

- The input to this software is similar to the previous one except that at additional column specifying the type of equipment is required. A sample input format is shown in Figure 16
- The output schema is displayed on the terminal as well as stored in a file named '*Load_Balance_Results.txt*'

```
######################## Load Balance Results ####################
Equipment on R - Phase:
A_3
F (3-ph)
F_2 (3-ph)
B
----------------------
Equipment on Y - Phase:
A_2
F (3-ph)
F_2 (3-ph)
C
----------------------
Equipment on B - Phase:
A
F (3-ph)
F_2 (3-ph)
D
E
########################### PHASE CURRENTS #######################
(For perfectly balanced load the magnitude of currents should be equal and the angles should be 120 apart)
Current drawn from R-Phase: 88.35∠-30.96 A
Current drawn from Y-Phase: 88.35∠89.03999999999999 A
Current drawn from B-Phase: 84.03∠214.36 A
#############################    END    ##########################
```

Figure 17: Version 5 - Sample Output

6.3 Version 6

- This is the final version for load balancing of Resistive and Inductive equipments.
- We know that the Software in Version 5 will take a long time to compute the schema in case there are a large number of reactive loads.
- I along with my mentor also figured out another working algorithm for Version 5 which was scalable for any number of loads but was a bit difficult to code.
- Moreover, in real life applications there was no capacitive load and all the loads were resistive or inductive in the Rebel kitchen.
- Hence, this software first divides the single phase loads in two categories and applies the algorithm of Version 4 for both of these separately.
- The output generated is the best possible Load Balancing schema for the given equipments.
- The input and output formats are same as those in Version 5 with the only change that Capacitive loads are not supported.
- This software is scalable to any number of resistive as well as inductive equipments as loads.

7 Load Balancing of Mixed Loads

- There are some loads which neither purely resistive nor purely reactive.
- They consume some amount of real and some reactive power given by their power factor.
- Their impedance is a complex number with non-zero real and imaginary parts.
- To balance these loads the best solution can be only given if we try all the permutations and choose the best one. However, as we know, this algorithm won't be scalable.

7.1 Version 7

This Version of the software is used to get a load balancing schema of any type of loads(Resistive, Capacitive, Inductive and Mixed)

7.1.1 Algorithm

- Since trying all the permutations is not scalable, a totally different algorithm is used in this case.
- First we obtain the admittance of all the equipment and arrange them in descending order of their magnitude.
- We know that the sum of all admittance is constant and admittance on each phase should tend to $avg\_value = (this\_sum)/3$.
- While allocating an equipment to a phase, we maintain 3 variables of the form $error\_in\_x$ which is the difference in the avg_value and current admittance on $x - phase$.
- The algorithm allocates each impedance to the 3 phases one by one and checks which error is reduced the most. That phase is finally allocated the impedance.
- After first allotment of elements we again run through all elements one by one 5 times.
- We temporarily relocate an element in the other two phases one by one and check the cost(as described in Version 5).
- If the cost is lesser than the previous we shift the element to the other phase permanently.

***This algorithm does not guarantee the perfect balancing schema as we are not trying all the permutations, yet the answer is extremely close or at times equal to the best case.*

7.1.2 Demonstration of the Software

	A	B	C	D	E	F	G
1	Machine/Fixture	Variable Name	Qty	Single/Three Phase	Power at Peak (kVA)	Power Factor	eading/Lagging
2	A		1	1	10	1	
3	B		1	1	10	0	Lagging
4	C		1	1	10	1	
5	D		2	1	10	0	Lagging
6	E		1	1	10	1	
7	F		1	3	10	0	Leading
8							
9							

Figure 18: Version 7 - Sample Input

```
######################## Load Balance Results ####################
Equipment on R - Phase:
A
D
F (3-ph)
-----------------------
Equipment on Y - Phase:
B
C
F (3-ph)
-----------------------
Equipment on B - Phase:
D_2
E
F (3-ph)
########################### PHASE CURRENTS #######################
(For perfectly balanced load the magnitude of currents should be equal and the angles should be 120 apart)
Current drawn from R-Phase: 101.64∠63.43 A
Current drawn from Y-Phase: 101.64∠183.43 A
Current drawn from B-Phase: 101.64∠303.43 A
#############################    END    ##########################
```

Figure 19: Version 7 - Sample Output

8 Finishing Up

- Finally the Versions which would be majorly used are:
  - Version 4: For Purely Resistive Loads
  - Version 5: For Resistive and Reactive Loads (Small Number of Reactive Loads Supported)
  - Version 6: For Resistive and Inductive Loads

- Version 7: For all types of loads including Mixed Loads

- All the software is developed in python and the executables of all the above listed versions are provided with the sample input and output formats.

References

[1] *https://commons.wikimedia.org/w/index.php?curid=5607023* By User: J J Messerly modification of original svg by User: Sirius A - File: 3-fas-spänningar.svg, Public Domain

[2] *https://commons.wikimedia.org/w/index.php?curid=24823731*, By Svjo - Own work, CC BY-SA 3.0

[3] *https://www.irjet.net/archives/V4/i3/IRJET-V4I3247.pdf*