Power Generation Laboratory 3 Report

Thomas Harley

B143091

March 4, 2021

The University of Edinburgh
Sanderson Building
Robert Stevenson Road
The King's Buildings
Edinburgh
EH9 3FB

1 Introduction

This lab involves **two tasks**. Task one is to test the operation of a synchronous generator in an isolated system. The generator will be connected to a three phase, star connected, resistive bank. The aim is to supply 200V (line) at 50Hz to the resistive bank at three different load settings [1]. The second task analyses the operation of a synchronous generator when connected to a grid system. The aim is to synchronise the generator to the grid and generate 300W at 1.0 power factor, and 200W at 0.8 power factor [1].

2 Task 1: Operation in an Isolated Power System

2.1 Explanation of how the System Operates

Figure 1 shows a detailed diagram of the full system. We are going to be using an induction motor to simulate our 'prime mover'. The induction machine acts as a steam turbine would in a real world system. Since we are only simulating energy generation, we are going to use a *three phase inverter* to drive our induction motor rather than a form of fuel like coal or gas as we would in a real system.

This inverter converts from three phase AC, to DC (using a three phase bridge rectifer) and then back to three phase AC (using a three phase inverter). A three phase, 400V (line), 50Hz power supply sends power to the inverter.

The inverter has a control circuit (*figure 1*) which sends timed 'on' and 'off' pulses to control the amplitude and frequency of the three phase AC voltage sent to the induction motor. The magnitude of this voltage is related to the airgap torque of the induction machine by the following equation:

$$(T_L + T_P) = \frac{180V_1^2}{2\pi N} \times \frac{sR_2'}{(sR_1 + R_2') + s^2(X_1 + X_2')^2} \tag{1}$$

The basic principle of an induction motor is it converts electrical power into mechanical power. As we increase our inverter voltage, torque increases, power increases and the rotational speed (ω) of the shaft also increases. The relevant formula here is:

$$P = T \times \omega \tag{2}$$

Where P is mechanical power, T is airgap torque and ω is rotational speed. This mechanical power rotates the shaft of the induction machine. Since the induction machine and the synchronous generator share the same shaft, the induction machine drives the generator.

The synchronous generator output is connected to the resistive bank. In order for the synchronous machine to generate electrical power a DC power supply is connected to the field winding of the synchronous generator. A diode bridge is connected between the power supply and the field winding to prevent any damage to the equipment due to a back EMF. The current from the DC supply I_f magnetises the field winding so that the synchronous generator can generate voltage and therefore power the resistive load. The back EMF of the synchronous generator is given by:

$$E \propto speed \times \phi_f \tag{3}$$

Where ϕ_f is the magnetic flux of the field winding and 'speed' represents the speed of rotation of the shaft (ω) linked to the induction machine . We also know that:

$$\phi_f \propto I_f \tag{4}$$

Where I_f is the current in the field winding generated by the DC power supply. Thus, the magnetic flux of the field winding is controlled by the DC power supply. Connecting these two relationships we can say:

$$E \propto speed \times I_f \tag{5}$$

Therefore, we can control the magnitude of the voltage that is fed to the resistive load in two ways. One by altering the DC power supply voltage, and therefore the current I_f, and two by changing the rotational speed of the shaft, which is controlled by the inverter.

Note that when we increase the voltage by increasing I_f we also increase the mechanical load on the induction motor which decreases the 'speed' and thus the frequency. Therefore, if we want to increase both voltage and frequency to meet a high resistive load it is best to increase the voltage of the inverter, supplying more torque and power from the induction machine and increasing the shaft speed.

We can control the frequency of the voltage generated by the synchronous machine according to the formula:

$$\omega_0 = \frac{2\pi f}{p} \tag{6}$$

Where p is the number of pole pairs of the induction machine (which in our case is two). ω_0 is the rotational speed of the shaft (in $rads^{-1}$) which can be controlled by the inverter and f is the frequency. So for our desired frequency of 50Hz we want an ω of ~1500rpm.

2.2 Task Procedure

Now that we have outlined the full system and the flow of power we can give a brief explanation of the procedure during the task. *We have to supply 200V (line) at 50Hz to the resistive bank for three different load settings.* Once we have set up the power system as outlined above (and in *figure 1*) we need to connect a power meter to one of the output phases of the synchronous generator. This will allow us to measure the frequency and magnitude of voltage being supplied to the resistive bank. The voltage we'll be measuring will be phase voltage. We know that:

$$V_{phase} = \frac{V_{line}}{\sqrt{3}} = \frac{200}{\sqrt{3}} \simeq 115V \tag{7}$$

Therefore we want to measure *115V (phase voltage)* on the power meter. Make sure the outputs of the synchronous generator are connected to the resistive load. Adjust the voltage of the inverter to generate an rpm in the shaft of ~1500rpm (according to equation 6). Turn on the DC power supply and the synchronous generator will begin to generate power due to the field winding. Before turning on any resistive load adjust the inverter and DC power supply to achieve a *stable 115V (phase) at 50Hz*. Whenever we adjust anything we should wait and give the system time to stabilise before taking any readings. We can allow a very small margin of error. Use the power meter to take readings. We can also use a handheld tachometer to get accurate readings of the shaft rpm.
Once the stable supply of 115V (phase) has been achieved repeat for the three load settings

on the resistive bank: low, medium and high. Each time adjust the inverter and DC power supply to achieve 115V (phase) at 50Hz. Notice that when we increase the load the output frequency and voltage go down. We must supply more power to bring the voltage back up. Once the experiment is completed, turn everything off in the reverse order that it was turned on. This is good practice for power systems.

2.3 Relation to Real World Power Systems

In this task an off-grid, isolated power system was simulated. Isolated power systems have a number of specific use cases. Many island communities make use of such systems where connecting to the grid is often not possible. One such example is the Canary Islands [2]. Power generation costs can often be higher for these systems than on the mainland and there can also be issues with stability. In the past hospitals often used isolated power systems as a backup option in the event of a power failure, however less hospitals employ this option now [3].

Isolated power systems are also used in developing nations where a large interconnected grid system does not exist. In India for example: 'many villages have been electrified through the use of renewable isolated power plants' [4]. Numerous studies have been conducted on the merits of using isolated power systems to electrify small villages.

The induction motor or "prime mover" in our experiment is driven by a three phase inverter drive and is not a steam turbine powered by some form of fuel or renewable energy. In the lab we can use the inverter drive to alter the torque and speed of the induction machine to affect the output frequency. In real world systems if power demand changes we can release more or less steam to change the speed of rotation of the turbine and keep the output frequency constant (equation 6). The low, medium and high load settings on the *'MOD-6020-R ITALTEC'* resistive bank can simulate the expected variation in load throughout the day that we would likely get in a real world power system. There is lower power demand while people are at work and higher power demand in the evenings when people are at home, cooking, watching TV, etc.

3 Task 2: Operation when Connected to the Grid

3.1 Explanation of how the System Operates

Figure 2 shows a detailed diagram of the second system. The setup is very similiar to the setup in task one. The three phase inverter connects to the induction machine which is tied to the synchronous generator along the same shaft. The field winding of the generator is connected to a DC power supply, with a diode bridge between them. However, the resistive load has been replaced and the output of the synchronous generator now passes through a three phase switch and connects to the grid (see *figure 2*) which is a three phase, 200V (line), 50Hz supply. This corresponds to a 115V phase voltage, which is what we need to achieve on the generator side for synchronisation. Lights are connected in parallel across the synchronising switch box. These can be used to check whether the voltage from the generator has the same frequency, magnitude and phase as the grid. They can also help us check whether the phase rotation of the three phases is correct. If all the lights don't flash on or off together we know the rotation is wrong.
We use the lights in combination with some instrumentation devices to synchronise our generator to the grid. A multimeter is connected to one of the three output phases of the synchronous

generator so we can measure voltage, power, and power factor. A three channel oscilloscope is also used. One channel is used to measure the generator side voltage and another to measure the grid side voltage. We also run one of the phases through a current transformer coil and the third channel is used to measure the voltage output of the current transformer, which is equivalent to the current of that phase. Its important to remember when connecting the probes that the same phase should be measured by all three oscilloscope channels.

3.2 Task Procedure

Now that the set up of all componentry and instrumentation is complete we can move onto the task procedure. The first step is to synchronise the generator to the grid. Increase the inverter voltage to increase the speed of the induction machine to ∼1500rpm as before. Turn on the DC power supply. Now observe the oscilloscope. With the grid off the oscilloscope channel showing current from the current transformer will be zero, since there is no load. The two other channels will be identical since the grid is off which means the generator side and grid side voltage is the same (the switch box acts as an open circuit).

Now we turn on the grid. Since the voltage, frequency and phase from the generator are not synchronised to the grid there will be a relative speed between the two voltages on the oscilloscope indicating a difference in frequency. This will also be indicated by a flickering of the lamps. We can now adjust the frequency and voltage to achieve 115V (phase) at 50Hz as we did in task one by adjusting the inverter which adjusts the speed of the induction machine. Speed is correlated to the output voltage's magnitude and frequency by equations 5 and 6 respectfully. We must also ensure that the phase rotation is correct. If all the lamps are flickering together then the phase sequence is correct but if they are not then this means the phase rotation must be corrected as described in the answer to question 7 in *Section 4*.

Once we know the phase rotation is correct we can adjust the frequency and magnitude of the generator output voltage to bring it in line with the grid. Once the oscilloscope and multimeter indicate we have achieved this we flick the switch on the three phase switch to connect the generator to the grid. The lamps should be off and the two voltage channels on the oscilloscope should be in phase with each other. The generator is now synchronised to the grid.

The final part of the task is to control the synchronised generator to produce *300W at 1.0 power factor* and *200W at 0.8 power factor* into the grid. We can use the multimeter to measure power and power factor. First we will control power. Since frequency is now fixed by the grid, the speed of the induction machine is also fixed (see equation 6). However, by increasing the torque we can increase the mechanical power input to the synchronous generator, (equation 2), which will increase our active power. Remember we have three phases so we want to measure $300/3 = 100W$ for the first part and $200/3 = 66.\dot{6}W$ for the second part.

The power factor can be controlled by altering the current of the field winding (I_f) by changing the DC voltage coming from the power supply. The power factor is represented on the oscilloscope by the phase difference between the voltage channels and the current transformer channel. At 1.0 power factor they should appear perfectly in phase, however due to instrumentation we might observe a slight difference. Adjust the power and power factor to achieve both specifications and then switch everything off in reverse order as we did in task one.

3.3 Relation to Real World Power Systems

In this task, a grid connected system was simulated. Large scale power networks in the UK and other countries utilise a grid connected system. When connected to the grid each individual generator has little to no control over the voltage and frequency of the overall system. We saw this in the laboratory as once we were synchronised to the grid we could no longer alter the speed and thus the frequency of the generator. We achieved a power factor of both 1.0 and 0.8. In a real world scenario it is desirable to achieve a unity power factor as there are lower power losses, less voltage drop in the line and systems operating at a higher power factor are more efficient [5].

In the laboratory we had two options to correct the generator phase rotation (see the answer to question 7 in *Section 4)*. We could swap two of the three phases of the generator or swap two of the three phases of the induction motor/ prime mover. However in a real world system it would not be possible to swap the phases of the 'prime mover' so normally we only have the first option.

4 Answers to Lab Manual Questions

1. *How will you control the speed of the induction motor?*
   We use the three phase inverter drive to control the speed of the induction motor. The inverter has a control circuit that can send "on" and "off" signals to control the three phase voltage output of the inverter. This voltage changes the torque of the induction motor (equation 1) which directly affects the speed (equation 2).

2. *At what speed (in rpm) should the prime mover drive the generator?*
   We can calculate this using equation 6:

$$\omega_0 = \frac{2\pi f}{p} = \frac{2\pi(50)}{2} = 50\pi \simeq 1500rpm \tag{8}$$

3. *When supplying the resistive load, how can you control the generator output frequency?*
   We can control frequency using the three phase inverter drive. Altering the voltage of the inverter output, using the control circuit, alters torque and power which changes the speed of the induction motor (equation 2). This change in ω alters the frequency according to equation 6.

4. *When supplying the resistive load, how can you control the generator output voltage?*
   We can control output voltage by increasing the DC power supply voltage, this will increase the field current I_f which according to equation 5 is proportional to the output voltage. Note though that increasing voltage this way also decreases frequency. Therefore, we can also increase the output voltage as outlined in question 3: altering the speed of the induction motor changes voltage as well as frequency (equation 5).

5. *What will happen if the resistive load on the generator is increased?*
   An increase in the resistive load causes an increase in output current. This leads to an increase in the reverse torque in the induction motor. The speed of the shaft drops causing a decrease in frequency and voltage according to equations 6 and 5 respectfully.

6. *When synchronising to the grid what will happen to the synchronising lights when:*

(a) *The voltages are correct but the generator frequency is 49Hz?*
The grid is supplying 50Hz while the generator is supplying 49Hz. This will result in the lamps flickering on and off.

(b) *The voltages and frequency are correct, and the generator voltage is in phase with the grid voltage?*
The generator is synchronised to the grid. All three lamps will therefore be off, given that the phase rotation is correct.

(c) *The voltages and frequency are correct but the generator voltage is 180°out of phase with the grid voltage?*
All three lamps will be on in this case, given that the phase rotation is correct.

(d) *The voltages, frequency and phase are correct, but the generator phase rotation is wrong (i.e: phase a leads phase b by 120°etc.)?*
In this case, all three lamps will **not** be on or off together (i.e: they will be out of sync with each other). Two lamps may be on while one is off.

7. *If the generator phase rotation is wrong, how would you correct it?*
We have two methods in the laboratory. The first option is to swap two out of the three phases of the generator. The second option is to swap two out of three phases of the induction motor/ prime mover. This second option is not available in real world applications.

8. *When synchronised to the grid how can you control the real power fed into the grid?*
When synchronised, since the frequency of the grid and the generator are in sync, the speed of the induction motor cannot change (equation 6). However by changing the voltage output of the inverter and thus the induction motor torque, we can increase the mechanical power being fed to the generator according to equation 2. This increases the real power fed into the grid.

9. *When synchronised to the grid how can you control the generator power factor?*
A big advantage of synchronous machines is how easy it is to control power factor. To do this we use the field winding current I_f. By changing the current of the rotor, which is controlled by the DC power supply, we can alter the power factor of the generator.

References

[1] The University of Edinburgh. *Power Generation Laboratory Manual.* (accessed: 04.03.2021).

[2] M. Uche-Soria and C. Rodríguez-Monroy. “Special Regulation of Isolated Power Systems: The Canary Islands, Spain”. In: *Sustainability* 10.7 (2018), p. 2572. URL: `https://search-proquest-com.ezproxy.is.ed.ac.uk/scholarly-journals/special-regulation-isolated-power-systems-canary/docview/2108862808/se-2?accountid=10673`.

[3] R. Munagala. “Isolated Power Systems for Hospitals”. In: *Consulting - Specifying Engineer* 41.5 (2007), p. 78. URL: `https://search-proquest-com.ezproxy.is.ed.ac.uk/trade-journals/isolated-power-systems-hospitals/docview/220593531/se-2?accountid=10673`.

[4] Rangan Banerjee M.V. Manoj Kumar. “Analysis of isolated power systems for village electrification, Energy for Sustainable Development”. In: 14.3 (2010), pp. 213–222. URL: `https://www.sciencedirect.com/science/article/pii/S097308261000030X`.

[5] Electrical Classroom. *Power Factor – Importance, Calculation and Correction techniques.* URL: `https://www.electricalclassroom.com/power-factor/`. (accessed: 03.03.2021).

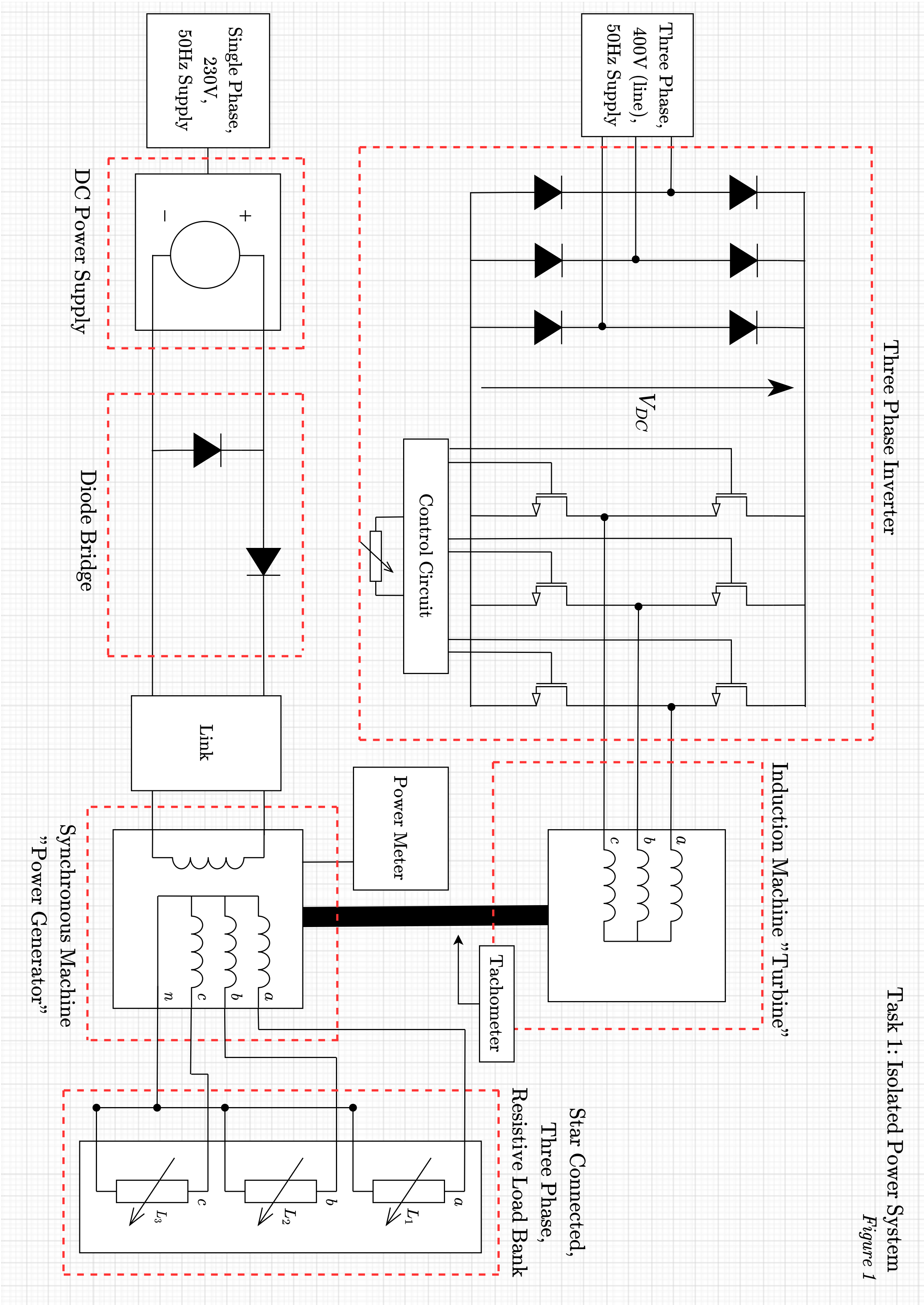

Figure 1: Isolated Power System

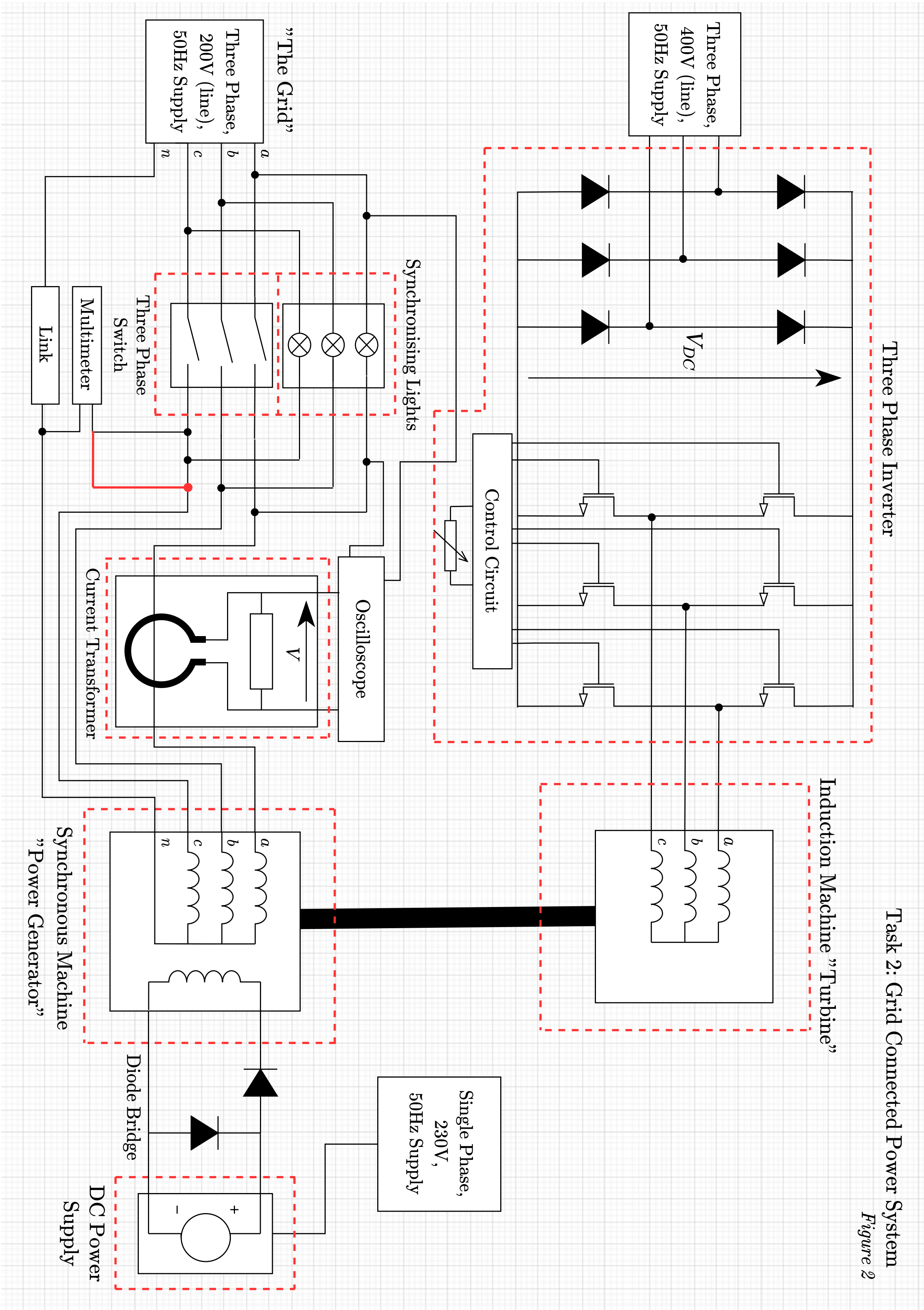

Figure 2: Grid Connected Power System