Commission 400Hz Power Supply

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for the degree of Bachelor of Science in Mechatronics Engineering.

Declaration

I declare that this dissertation is my own, and all external ideas and input is referenced. It is being submitted for the degree of Bachelor of Science in Engineering in the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

Signature of Author ....

University of Cape Town, 19th October 2004

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Abstract

An existing 400Hz generator set which is mechanically linked to a 15 kW induction motor needed to be tested so that it could be used to generate 400Hz power for various radar systems in the department. The 400Hz generator used was obtained from an Mirage F1 and coupled with the induction machine through a special coupling unit built under contract outside UCT.

The 400Hz power supply was set up in the machines where several tests were carried out to determine the performance characteristics of the system .Since this particular design had not been tested before, a large part of this thesis involved identifying and sorting out operational problems with the 400Hz supply. After the 400Hz power supply system had reached a point where it was working efficiently, implementation designs such as the cooling mechanism and the platform design where done.

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1 Introduction

This report concerns the procedure that was followed in getting the 400Hz Power supply for the UCT Radar Remote Sensing Group to a stage at which it would be commissioned for use.

1.1 Background of project

UCT has been supplied with number of very useful 400Hz generators by the defence force. The Radar department could put these generators to good use to drive some of the equipment currently available such as the Pillbox Antenna for the new SASAR II project. The 400Hz power supply system will feed two laboratories.

The generators were installed on Jet fighters to supply power to the radar systems on the decommissioned planes. The original prime movers were the actual jet engine turbines that obviously had variable throttle and therefore the 400Hz generator had a variable input speed range. Using an electro-mechanical drive system, a constant 400Hz output frequency was produced. Since the department had no jet engine turbines at their disposal, the original prime mover was replaced with a cheaper and readily available prime mover, induction motors. After the specifications of the 400Hz generator were analysed, a 400Hz power supply unit was designed which would use a 15kW induction motor as the prime mover. This thesis is the implementation of that design.

The design to be implemented consists of 15kW induction motor mechanically linked to a 400Hz generator set (refer to figure 1). Two types of generators exist, one from a Mirage F1 plane that is the one currently coupled to the induction motor and the second from a decommissioned Radar Jammer Pod that is in storage.

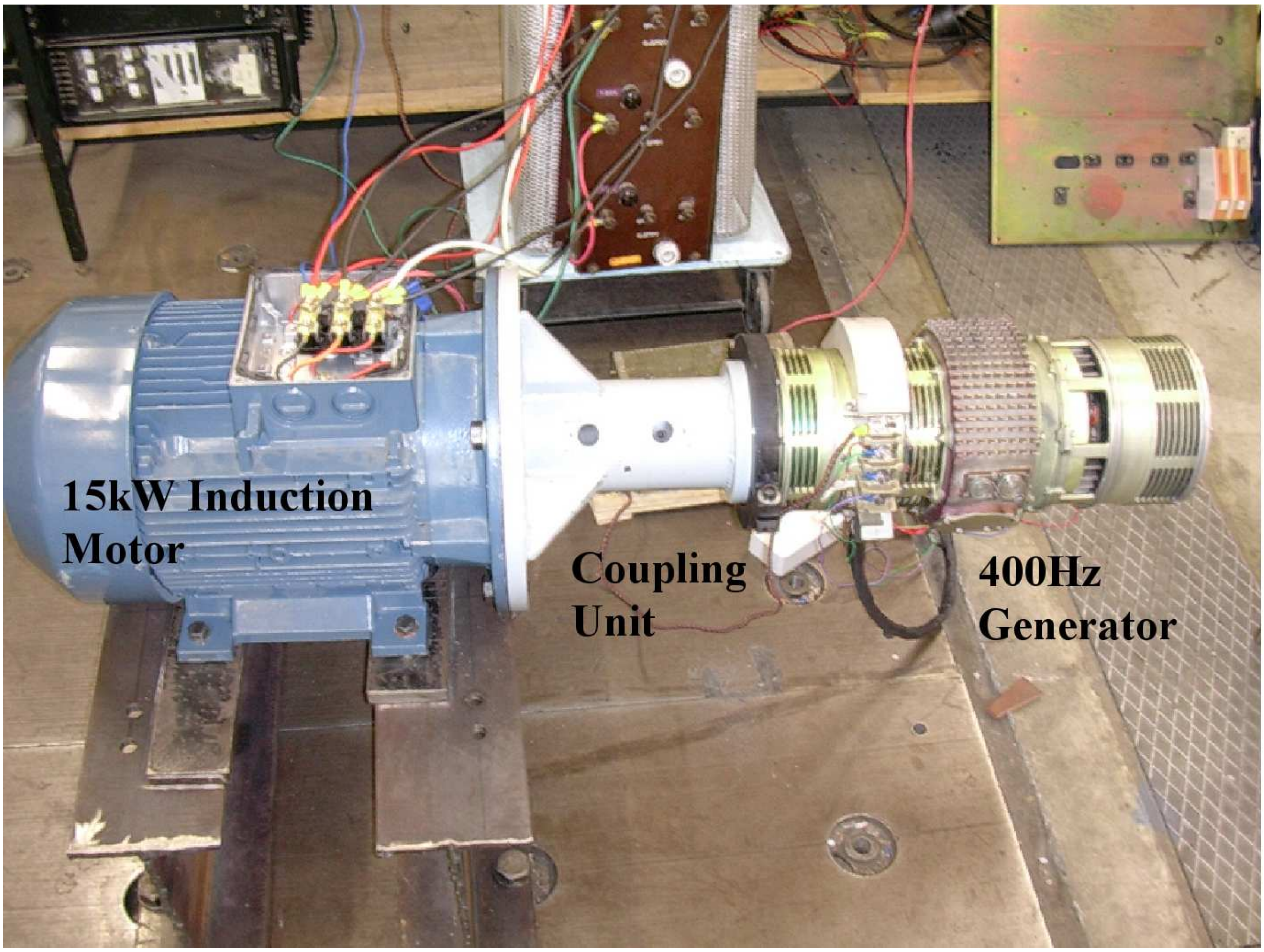


Figure 1: 400Hz Power Generation set

1.2 Components of the 400 Hz power supply

1.2.1 The prime mover - 15kW induction motor

The first tests will require testing the prime mover, that is the induction motor alone. This is done in order to determine the characteristics of the motor and also to determine the equivalent circuit of the motor. The no-load and locked rotor tests will be carried out to determine these parameters.

The no-load test of an induction motor gives information about exciting current and rotational losses while the blocked-rotor test gives information about leakage impedances. The equivalent circuit obtained is used to predict the performance characteristics of the induction motor. The performance characteristics in the steady state are the efficiency, power factor, rated torque, starting torque, and starting current[1]. After the performance characteristics of the motor have been established using the no-load test and the blocked rotor test, the tests shifted to determining the performance of the generating system as a whole.

1.2.2 400Hz Constant frequency generator

The constant frequency generator is the most important component of the power supply. Chapter 2 of the report looks at the 400Hz power generator in detail providing detailed information on the generator's characteristics, assembly, operation and connections.

The 400Hz generator consists of:

- Constant frequency alternator
- Regulator
- Adjusting unit
- 28V supply unit

The constant frequency alternator features three main parts:

- the alternator, at the front (side of input shaft)
- the electro-mechanical constant speed drive, in the centre
- the Eddy current brake assembly, at the rear

The generator constituted of an independent source of 400Hz, three phase, A.C power for an 115/200V aircraft power system. In this case, the generator will be used to provide 400Hz power to two laboratories for the radar department. The constant frequency generator produces 15k VA at a driving speed between 5600 and 8320 rpm and 12k VA at a driving speed between 2680 and 5600 rpm. Since the prime mover we are using now is a 15kW induction motor with a rated speed of 2940 rpm at 50Hz, the output power will be 12k VA. The 400Hz generator consists of an electro-mechanical constant speed drive that converts input speed into constant speed and an alternator the inductor of which is driven at a constant speed by the constant speed drive[2].

The regulator maintains a three-phase voltage of 115/200V ± 2% and a 400Hz frequency ± 1% at a constant value whatever the load and driving speed (between 2680 and 8320 rpm) may be. The adjusting unit is intended to remote adjustment of the output voltage. In this case 200V output voltage varied between 190V and 206V using a potentiometer[2]. The 28V signal unit provides 28V needed to switch the relays on in the regulator in order for it to work.

1.2.3 Coupling unit

This is the mechanical link between the 15kW induction motor and the constant frequency generator. The operating range of the 400Hz generator is between 2680 and 8320 rpm. Since the induction motor has a rated speed of 2940 rpm when connected to a 50Hz power supply, which is within the operating speed of the generator, the coupling unit connects the two shafts directly through a jaw coupling, refer to figure 14.

After the working of the components of the 400Hz power supply was understood, the emphasis moved to the main part of this thesis which was the testing of the 400Hz power supply in order to evaluate it's operating conditions. The testing procedure is explained in detail in the following chapter, chapter 3.

1.3 Testing procedure

Commissioning of the 400Hz power supply involved testing the components of the system, finding out the faults with the components and then dealing with them so that the system can reach a stage in which it would be implemented.

1.3.1 Testing the 15kW induction motor

The preliminary tests involved testing the prime mover alone that meant that the 400Hz generator had to be detached from the system. These tests were done in order to determine the equivalent circuit parameters of the induction motor. The parameters provide a better understanding of the motor characteristics. The no-load and blocked-rotor tests were carried out to determine these parameters.

The parameters of the equivalent circuit are:

V_1= per-phase terminal voltage

R_1 = per-phase stator winding resistance

X_1 = per-phase stator leakage inductance

X_2 = per-phase rotor leakage inductance

R_2 = per-phase rotor winding resistance

R_C = core loss in the machine

X_M = magnetising reactance

i_1 = line current

After the preliminary tests were carried out and the values of the parameters were calculated, the emphasis shifted to testing the whole generator. But like most projects, unexpected issues arise. The issues that came up and which had to be dealt with before the testing of the whole system could be done where: the removal of the coupling unit and the stabilisation of generation unit.

1.3.2 Stabilising the Unit and Removal of Coupling unit

Stabilisation of generation unit involved fitting a stud or screw through the mounting pin on the 400Hz generator. The stud was fitted into place on the coupling unit by drilling a hole on the unit in which the stud would be held firmly. This was done because this arrangement prevents the whole 400Hz generator from twisting when the induction motor is turned on. This was because the only thing that holds the generator firmly to the coupling unit is a split lock ring.

The success of the stabilising procedure depended on the successful removal of the coupling unit in the first place. Since the external contractors considered the construction of the coupling unit as a small job, there was no information on the removal of the coupling unit. The only information available was a design diagram for the unit refer to figure3 which was faxed to us. The design diagram was used to come up with a removal procedure of the coupling unit that is explained in detail in section 3.2.2.

1.3.3 Faulty wiring and the Cooling problem

The whole system was put through a preliminary test run after the stabilisation and removal issues had been dealt with, but this also brought about other unexpected issues to deal with. These issues were faulty wiring and a cooling problem. The faulty wiring problem was noticed because the as soon as the 28V supply unit which supplies power to the relays in the regulator was plugged in, there was no click sound that represents the switching of the relays. After this was sorted another wiring problem was noticed; though the regulator was working now, the output voltage and frequency values were wrong. This was due to the fact that the wiring in the connector that was replaced on the regulator was mismatched. This problem was also dealt with .

Then the next test run produced a clear issue of the generator overheating. When the generator was installed on the plane, it was force cooled to prevent it from overheating like it did during the test. To try improve the conditions, a duct fan was used with no real change in results. But since the generator overheated during the test run, there was fear that the oil that had been idle in the generator had oxidised. This lead to the refill of the lubrication oil in the generator(refer to section 3.2.4).

1.3.4 Faulty Electro-mechanical drive system

After these clear issues had been dealt with, the major problem with the generator was noticed. Ideally, the outputs of the 400Hz power supply would be a voltage of 115/200V ± 2% and a frequency of 400Hz ± 1%. In this case the generator seemed to be ”hunting” for the correct speed to produce 400Hz. The control of the speed of the generator is done by the electro-mechanical; something was causing it to malfunction. The problem was that one of the speed control methods was not implemented. The generator uses three methods of speed control, the main method is the clutch mechanism but this is supported by the eddy current braking system and frequency limiting resistors which come in if the speed change is to fast. The generator worked fine only after all three speed control methods were employed (refer to section 3.2.6).

1.3.5 Testing of the whole Generator system

The major part of this project was testing the performance of the constant frequency generator. This meant putting the system together in the lab, that is the adjusting unit and the regulator with their corresponding wiring where connected to the 400Hz generator. Before the system was put together the wiring available was checked for continuity and the problems with the wiring harness were dealt with.

After the components were connected, the generator was run through the tests to gauge its performance. These tests were the following:

- Testing if the regulator is producing ± 2% of the output voltage that is 200V and also whether the output frequency is within the ± 1% of 400Hz. This turned out to be a big problem in which the generator was ”hunting” (refer to section 3.2.6).
- Testing the response of the generator at different amounts of load then gathering the 400Hz generator’s efficiency at these loads and also the maximum loading on the generator (refer to section 3.3).

These tests where carried out to determine the stability of the entire system.

1.4 Implementation Design of 400Hz Power Supply

This project will lead to the eventual commissioning of the 400Hz supply system. This will involve adding the star/delta starter system already installed on level six to the system. For safety precautions circuit breakers need to be added. An emergency switch is available on the panel housing the star/delta starter system for remote starting of the system.

1.4.1 Starter Mechanism

In this section the attributes of using starters in general and star/delta starters in particular are explained in detail. The basic aim of the starters is to deal with the high currents and torques at start up which cause disturbances on the supply line. After the operation of the starter was explained, the circuit diagram of the star/delta starter and it’s connection points to the power supply and induction motor where shown (refer to section 5.1).

1.4.2 Cooling Mechanism

Since it was established that the cooling of the generator is extremely vital, a design of a suitable cooling mechanism was done. The design consists of a suitable centrifugal fan blowing air through the ventilation openings of the generator at the required flow rate of more than 358 cubic feet per minute (refer to section 5.2).

1.4.3 Platform Design

The 400Hz power supply will need to sit on a platform of some kind. The main requirement of the platform was that the supports of the platform be all under compression. This was taken into account and a suitable platform was designed (refer to section 5.3).

1.5 Conclusions and Future works

Based on the information in the previous chapters, the following conclusions and future works have been drawn.

1.5.1 Conclusions

1 The 400Hz power supply works efficiently up to 7400 W

The 400Hz power supply will safely and efficiently produce 3 phase, 400Hz power for the radar laboratories up to a load of 7400 W.

2 Rating on the starter mechanism must be changed

The star/delta starter has been rated to a maximum input power of 7500 W. But the 400Hz power supply can safely take a load of 7400 W which requires an input power of 9100 W.

3 Wiring must be completely redone

Before the 400Hz power supply system is commissioned, the wiring of the whole system must be redone to the correct standards.

4 Frequency resistors limit loading of the system

What ever load is added to the 400Hz power supply essentially adds to the 3 kW load already present on the generator due to the frequency limiting resistors. This limits our load range.

1.5.2 Future works

All the future works described in this section must be done before the 400Hz power supply is commissioned.

1 The starter mechanism must be tested

An automatic star/delta starter is currently implemented on level six which needs to be taken down to the machines lab for testing with the 400Hz supply system and the rating on the star/delta starter must be changed so that the generator can be loaded with bigger loads that require an input power of more than 7.5 kW.

2 Cooling mechanism must be implemented

During testing the running time of the generator was restricted to 20 minutes to prevent overheating.A duct fan with an air filter will blow air into the inlets of the generator and extraction fan will be connected to the outlet.

3 Platform must be constructed

The platform design described in section 5.3 must be constructed.

4 All external circuits must be placed in one box

Currently, the 28 V signal supply unit and the adjusting unit are housed in separate boxes. To make the wiring arrangement more efficient instead of the current arrangement where wires go in all directions, all external circuits should be housed in one unit.

5 Wiring must be completely redone

The wiring harness that is currently available had proved to be unreliable. Before the 400Hz power supply is commissioned the wiring harness of the system needs to be completely redone to the correct standards.

2 Components of the 400Hz Power Supply

This could be taken as the litreture review section. In this section each component of the 400Hz power supply was analysed in detail in order to have a better understanding on how each component worked. This background information on each component helps give a better understanding on how the system works as a whole and therefore provide more insight when an expected problems arises during the testing phase of the power supply system.

2.1 The Prime mover - 15 kW induction motor

2.1.1 General

The induction motor consists of a stator and a rotor mounted on bearings and separated from the stator by an air gap. The difference between dc motors and the induction motor is that, in induction motors both the stator winding and the rotor winding carry alternating current. The alternating current (ac) is supplied to the stator winding directly from the supply and to the rotor winding by induction - hence the name induction motor[1].

The rotor winding may be either of two types, the squirrel cage type or the wound rotor type. The squirrel cage winding consists of aluminium or copper bars embedded in the rotor slots and short circuited at both ends by aluminium or copper end rings. The wound rotor winding has the same form as the stator winding. The terminals of the rotor windings are connected to three slip rings. Using stationary brushes pressing against the slip rings, the rotor terminals can be connected to an external circuit. It is obvious that the squirrel cage motor is simpler, more economical and more rugged than the wound rotor motor[1]. For this reason, the induction motor used as the prime mover for the 400Hz power supply is a squirrel cage motor.

2.1.2 Running operation

If the stator windings are connected to a three-phase supply and the rotor circuit is closed, the induced voltages in the rotor windings produce currents that interact with the air gap field to produce torque. The rotor eventually reaches a steady-state speed n that is less than the synchronous speed $n_S$at which the stator rotating field rotates in the air gap[1]. In the case of the motor being used, it's n = 2940 rpm at an n_S = 3000 rpm. It is obvious that at n = $n_S$there will be no induced voltage and current in the rotor circuit and hence no torque[1]. The synchronous speed of the motor is obtained from the equation below

$$n_S = \frac{120 \times \text{frequency}}{\text{poles}} \qquad (1)$$

The induction motor being used is a two pole machine running at 50Hz hence an n_S of 3000 rpm. The difference between the rotor speed n and the synchronous speed n_S of the rotating field is called the slip s and is defined as[1]

$$s = \frac{n_S - n}{n_s} \tag{2}$$

This gives us a slip of 2% for the 15 kW induction motor being used. If you were sitting on the rotor, you would find that the rotor was slipping behind the rotating field by the slip rpm = n_S - n = s×n_S. The interaction between the stator magnetic field and the rotor magnetic field can be considered to produce the torque. As the magnetic fields tend to align, the stator magnetic field can be visualised as dragging the rotor magnetic field[1].

2.1.3 Equivalent circuit model

An equivalent circuit model is developed so that it can be used to study and predict or in this case verify the performance of the induction motor with reasonable accuracy. There are various configurations for the equivalent circuit but the configuration shown below is the most convenient to use for verifying the performance of the induction motor supplied by the manufacturers[1].

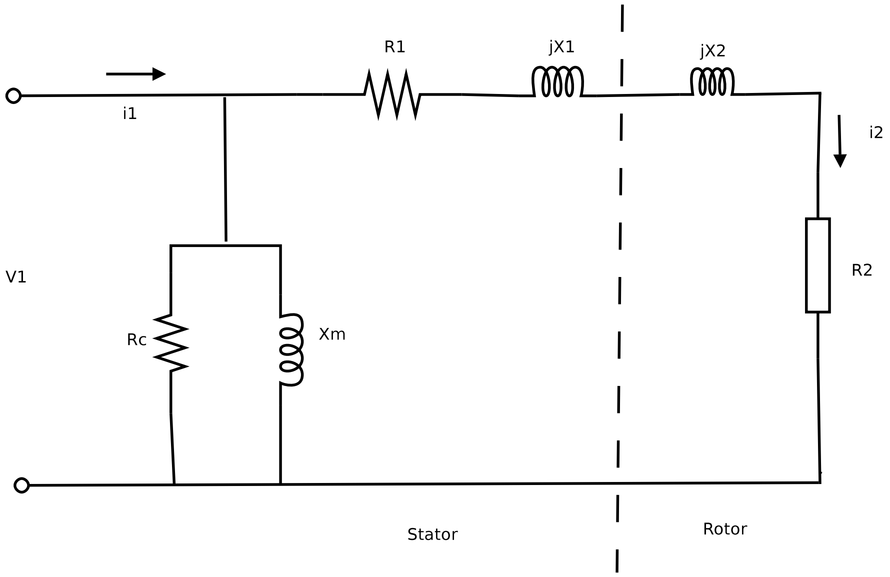


Figure 2: Equivalent Circuit

The parameters of the equivalent circuit are:

V_1= per-phase terminal voltage

R_1 = per-phase stator winding resistance

X_1 = per-phase stator leakage inductance

X_2 = per-phase rotor leakage inductance

R_2 = per-phase rotor winding resistance

R_C = core loss in the machine

X_M = magnetising reactance

i_1 = line current

These values are determined from the results obtained from the no-load test, a blocked-rotor test and from measurements of the dc resistance of the stator winding. The no-load test gives information on exciting current and rotational losses. The blocked-rotor test gives information on leakage impedance[1].

2.1.4 15 kW induction motor

A 15 kW induction motor was selected as the prime mover for the 400Hz power supply. The selection criteria followed was as follows:

The 400Hz generator has the following specifications on it's name plate

Table 1: Generator specifications

Parameter	Value	Units
Voltage	200	V
Rated current	43.5	A
Frequency	400	Hz
Speed range	2680 - 8320	rpm
Rated power	15	k VA
Phases	3	
Power factor	0.75	

From the specifications, the real power P_R= 15 $\times$0.75 = 11.25 kW. Hence the prime mover must be able to supply more power than this. This suggests that a 15 kW induction motor is more than adequate. But note that this does not include efficiency. The induction motor selected is a Siemens Energy-saving motor, the 1LA7 164-2AA. This is a 3 phase, 15 kW, 3000 rpm, 2 pole, 50 Hz squirrel cage motor in an aluminium housing. The induction motors specifications obtained from the manufacturers are tabulated below.

[3]

Table 2: Operating data at rated output

Parameter	Value	Units
Rated voltage	400	V
Rated current	26.5	A
Connection	Delta	
Frequency	50	Hz
Rated output	15	kW
Speed at rated power	2940	rpm
Efficiency at full load	90	%
Efficiency at 3/4 load	90.2	%
Power factor	0.90	
Rated torque	49	Nm
Weight	77	kg

[3]

Table 3: For Direct-on-line starting as multiple of rated output

Parameter	Value
Starting torque	2.2
Starting current	6.6
Stalling torque	3.0

The first tests that were done in this project where no-load and blocked-rotor tests on the induction motor. These tests provided us with the operating characteristics of the 15 kW induction motor. The important operating characteristics in the steady state are the efficiency, power factor, current, starting current, rated torque and slip. These tests were carried out to validate the specifications shown in table 2 and table 3 to a reasonable accuracy.

2.2 The Coupling unit

This is the mechanical link between the 15kW induction motor and the constant frequency generator. The operating range of the 400Hz generator is between 2680 and 8320 rpm. Since the induction motor has a rated speed of 2940 rpm when connected to a 50Hz power supply, which is within the operating speed of the generator, the coupling unit connects the two shafts directly through a jaw coupling.

The coupling unit consists of:

- Motor flange plate
- 4 off Gussets
- Front flange with 2 off ball bearings and adapter for alternator
- 1 off jaw coupling
- 1 off shaft with internal spline (nitrided)
- 1 off split lock ring with 2 off bolts[4]

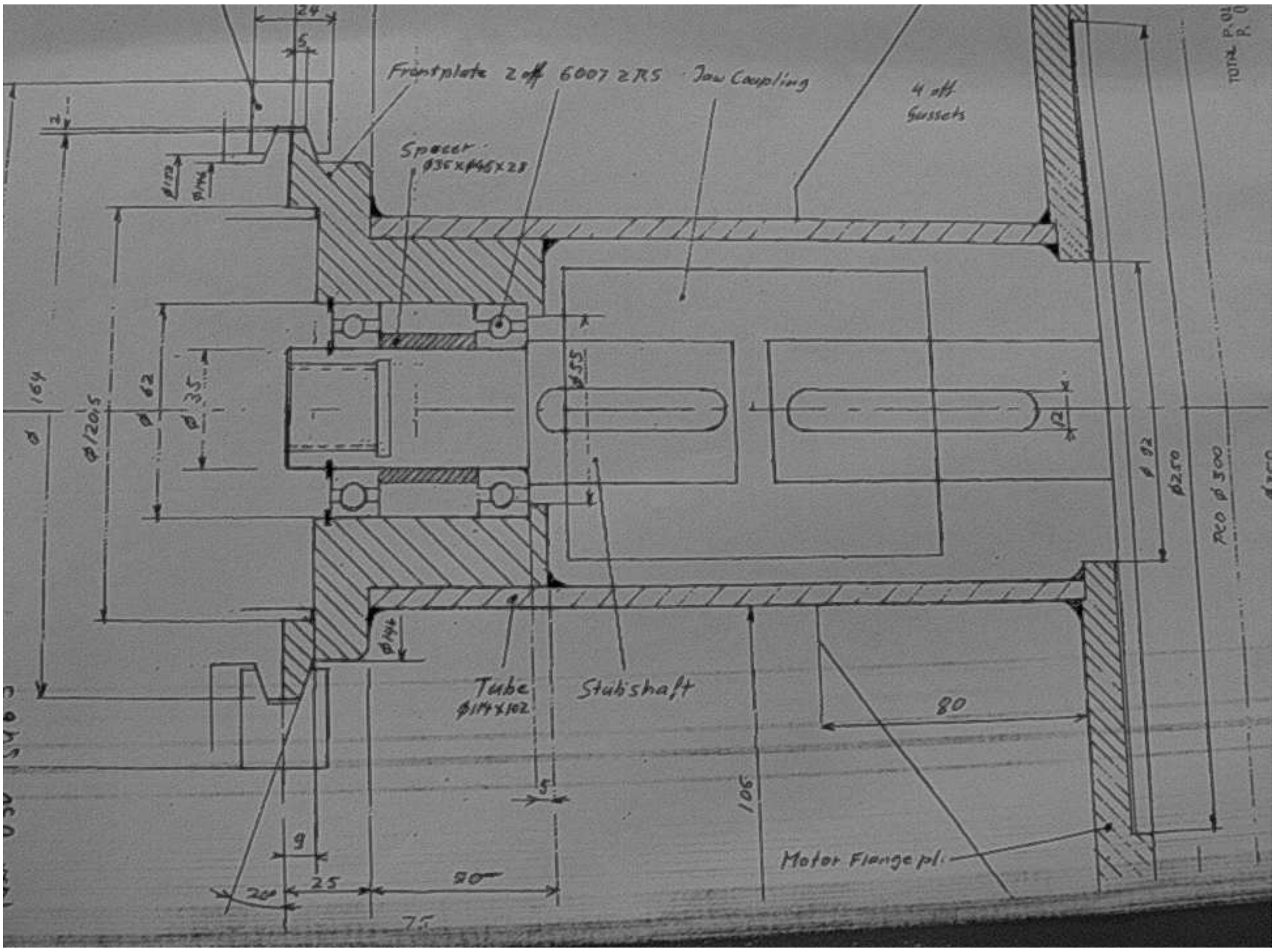


Figure 3: Coupling Unit design diagram

[5]

2.3 The Constant Frequency Generator

2.3.1 General

The constant frequency generator is the most important component of the power supply. The 400Hz generator consists of:

- Constant frequency alternator
- Regulator
- Adjusting unit
- 28V signal unit

The generator constituted of an independent source of 400Hz, three phase, A.C power for a 115/200V aircraft power system. The constant frequency generator produces 15k VA at a driving speed between 5600 and 8320 rpm and 12k VA at a driving speed between 2680 and 5600 rpm[6]. Since the prime mover we are using now is a 15kW induction motor with a rated speed of 2940 rpm at 50Hz, the output power will be 12k VA. The 400Hz generator consists of an electro-mechanical constant speed drive, which converts input speed into constant speed and an alternator the inductor of which is driven at a constant speed by the constant speed drive[6].

The regulator maintains a three-phase voltage of 115/200V ± 2% and a 400Hz frequency ± 1% at a constant value whatever the load and driving speed (between 2680 and 8320 rpm) may be. The adjusting unit is intended to remote adjustment of the output voltage. In this case 200V output voltage varied between 190 V and 206 V using a potentiometer[6]. The 28V supply unit provides 28V needed to switch the relays on in the regulator in order for it to work.

2.3.2 Characteristics[7]

Thermal Conditions

Constant frequency generator

- Maximum: +80^{0}C
- Minimum: -50^{0}C

Regulator

- Maximum: +85^{0}C
- Minimum: -50^{0}C

Power

Rated: 15 k VA

- N > 5600 rpm: 15 k VA
- N < 5600 rpm: 12 k VA

Cooling

Forced ventilation (3000 Pa): 275 cfm on alternator
358 cfm on brake   cfm = cubic feet per minute

Driving speed range

Maximum rate: 8320 rpm

Minimum rate: 2680 rpm

Regulation

Voltage: 115/200 V ± 2%

Frequency: 400Hz ± 1%

Rated current: 43.5 A

Power factor from 0.75 lagging to 1

Voltage adjustment provision: 190 to 206 V

Overloads from speed stabilised at 43.5A

- For 2 min: 65A
- For 5 secs: 87A

Short-circuit current for 5 seconds

130A < SCC < 305A

Driving torque at 15 k VA

- 1st range: 2680 < N < 5500: 77.92 Nm
- 2nd range: 5500 < N < 8320: 30.39 Nm

Direction of rotation

Counterclockwise when looking at end of constant frequency generator driving shaft.

2.3.3 Assembly

The 400Hz generator consists of the constant frequency alternator, regulator, adjusting unit and 28V supply unit. The generator constituted of an independent source of 400Hz, three phase, A.C power for a 115/200V aircraft power system[2].

1. Constant frequency alternator

The constant frequency alternator features three main parts:

- The alternator, at the front
- The electro-mechanical constant speed drive, in the centre
- The eddy current brake assembly, at the rear[2]

2. Regulator

The regulator is a rectangular box with five connectors for plugging in:

- constant frequency alternator (J1a)
- electrical generator external circuits (J2b)
- frequency limiting resistors (J4d)
- test sets (J3c and J5e)

It also has three covers of fuse holders.The various printed circuit boards for various functions such as frequency detection, torque limitation, clutch control, voltage regulation and so on, are housed within the box.[2]

3. Adjusting unit

It is a rectangular box featuring a potentiometer and is connected to the regulator through J2b [2].

4. 28V signal unit

It is a rectangular box featuring 28V supply circuit and is connected to the regulator through J2b[2].

2.3.4 Operation

2.3.4.1 Constant frequency alternator

The constant frequency generator is capable of delivering permanently a power of 15 k VA with a power factor between 0.75 lagging and 1, with driving speed between 5600 and 8320 rpm. But for a driving speed between 2680 and 5600 rpm, 12 k VA is produced[6].

It consists of an electro-mechanical variable speed drive, which converts the variable input speed into constant speed of an alternator, the inductor of which is driven by the constant speed drive. The constant speed drive is designed to deliver a constant rotational speed to the alternator, whatever the input speed from the power take off may be. This is achieved via 2 differential gears D1 and D2 and the Eddy current brake unit controlled by the ”frequency regulation” system of the alternator[6].

The regulator controls and monitors the excitation currents of:

- Alternator exciter
- Eddy current brake unit
- Clutch

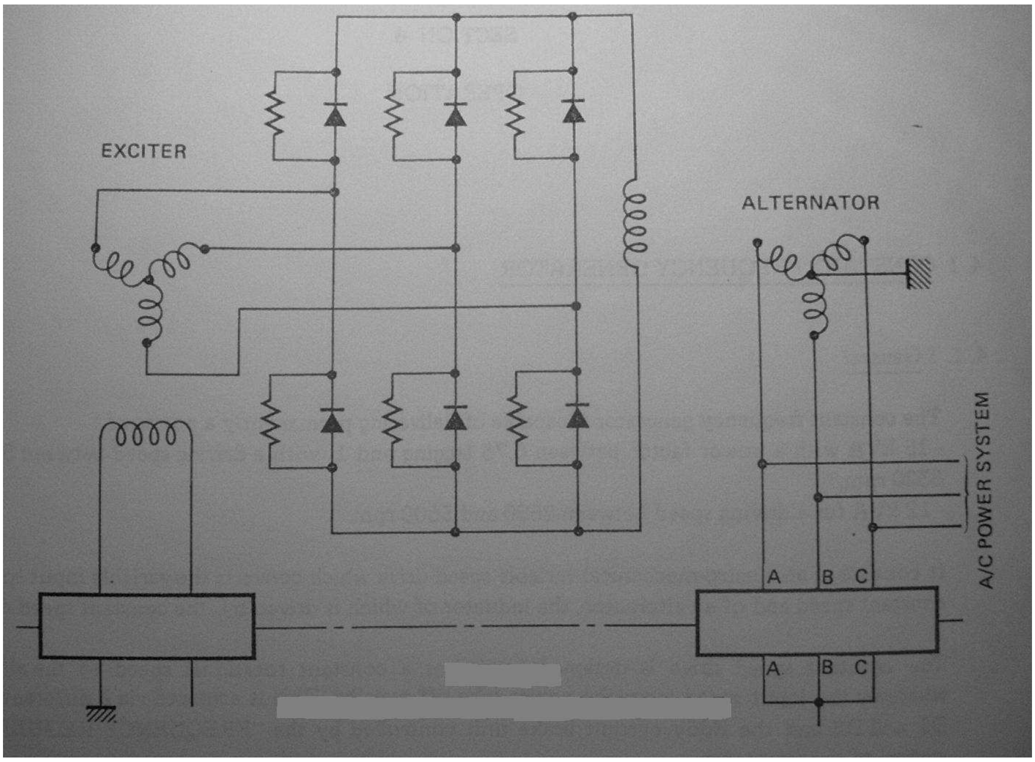
So as to obtain at the alternator output:

- A three phase voltage of 115/200 V ± 2%
- A frequency of 400Hz ± 1%

Whatever the power output of the alternator may be.[6]

Alternator

It is a rotary field winding alternator, which is supplied with D.C. power from the rotary armature of the exciter after rectification through a full-wave rectifier bridge, consisting of six diodes mounted on a rotary board[6].



[redacted]

Figure 4: Alternator operation principle

[8]

The exciter inductor is supplied from a permanent magnet generator (PMG) after voltage is seen by the ”voltage regulation” system of the regulator. The alternator must supply a constant frequency three-phase output voltage. The frequency of the alternating current delivered by the alternator depends on:[6]

- Number of pairs of poles (P)
- Rotational speed of the rotor (N rpm)

The alternator inductor has six poles; to obtain the 400Hz frequency(F) it must be driven at a rotational speed of:

$$N = \frac{F \times 120}{P} = \frac{400 \times 120}{6} = 8000\, rpm \qquad (3)$$

As the input rotational speed of the constant frequency generator is variable, to obtain a 8000 rpm constant speed, the alternator inductor is driven by the electro-mechanical speed drive[6].

Electro-mechanical constant speed drive

Its purpose is to deliver a constant rotational speed to the alternator whatever the input speed from the prime mover. It includes a two differential gear D1 and D2 system and an Eddy current brake controlled by the ”frequency regulation” system of the regulator.

The input shaft (E), turns at a variable speed and is directly connected to differential D1. The D1 differential output drives the alternator inductor (A), the other output is directly coupled to the armature (C) or ”cup” of the Eddy current brake. To keep constant rotational speed of the alternator at 8000 rpm, it is necessary to:

- reduce more or less the Eddy current brake cup rotational speed by varying slippage between cup (C) and brake inductor (F) which is locked by free-wheel (RL);

- cause cup (C) to rotate in reverse direction relative to input speed at variable speed (according to input speed). Reversal of direction of rotation of cup (C) is possible by driving the brake-inductor (F) in the reverse direction of input shaft.

A second differential D2 acts as a speed set-up change-over gear and is controlled by clutch (B). The Eddy current brake unit’s operating principle is based on Lenz’s law. When the inductor and the cup turn at different speeds, the rotating magnetic field created by the inductor produces Eddy currents within the cup. These currents generate a torque tending to oppose its originating cause i.e to suppress the slippage effect consecutive to the different rotational speeds of the inductor and the cup. It is possible to control the rotational speed of the cup by adjusting the magnetic field of the inductor[6].

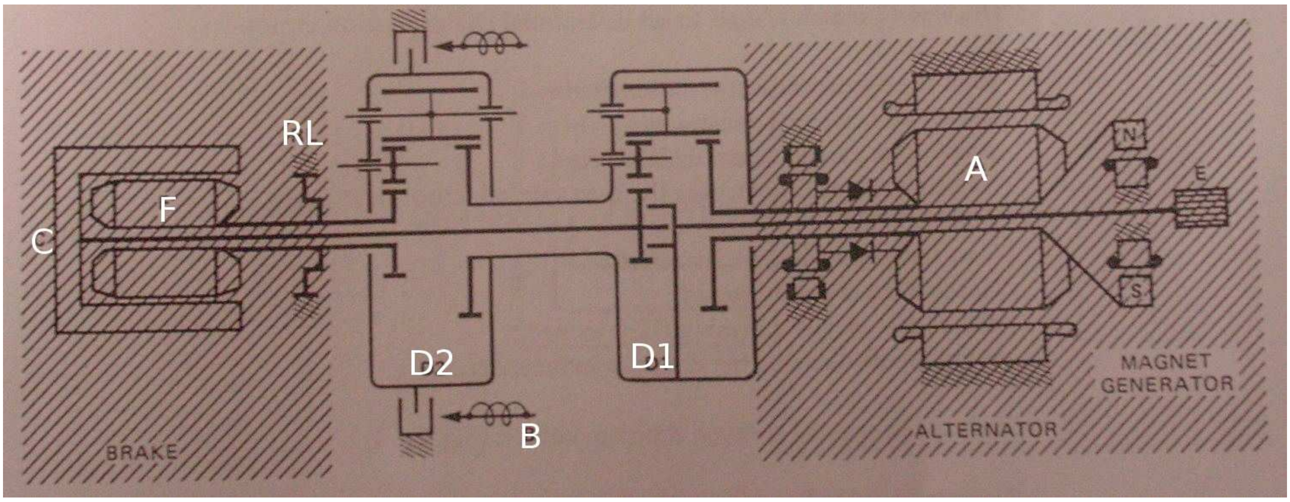


Figure 5: Principle of operation of speed drive

[9]

2.3.4.2 Regulator The regulator monitors and controls excitation currents of alternator exciter, eddy current brake inductor and clutch so as to obtain a three phase voltage of 200 V ±2% and a 400Hz frequency ±1% whatever the driving speed (between 2680 and 8320 rpm) and the alternator output may be[2].

2.3.4.3 Adjusting unit

The adjusting unit is intended to remote adjustment of the output voltage. In this case 200V output voltage varied between 180V and 220V using a potentiometer. The circuit arrangement is shown in figure 6 [2].

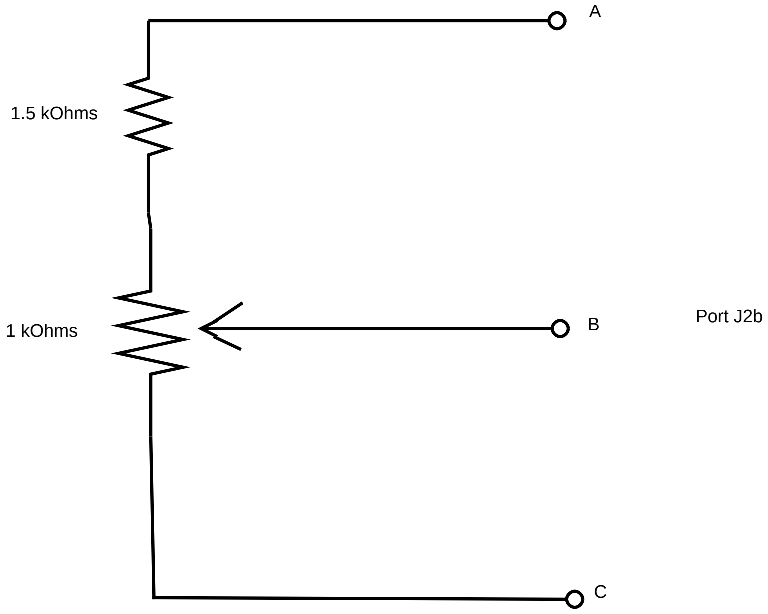


Figure 6: Adjusting Unit

[10]

2.3.4.4 28V signal unit

The 28V supply unit provides 28V needed to switch the relays on in the regulator in order for it to work. As shown in the figure below, the mains supply voltage is stepped down by a transformer and then rectified through a standard bridge and smoothing capacitor. The 25V dc is then regulated using an LM317L regulator chip with a few resistors which produces a near perfect, consistent 28V signal voltage[10]. The circuit diagram is shown in figure 7:

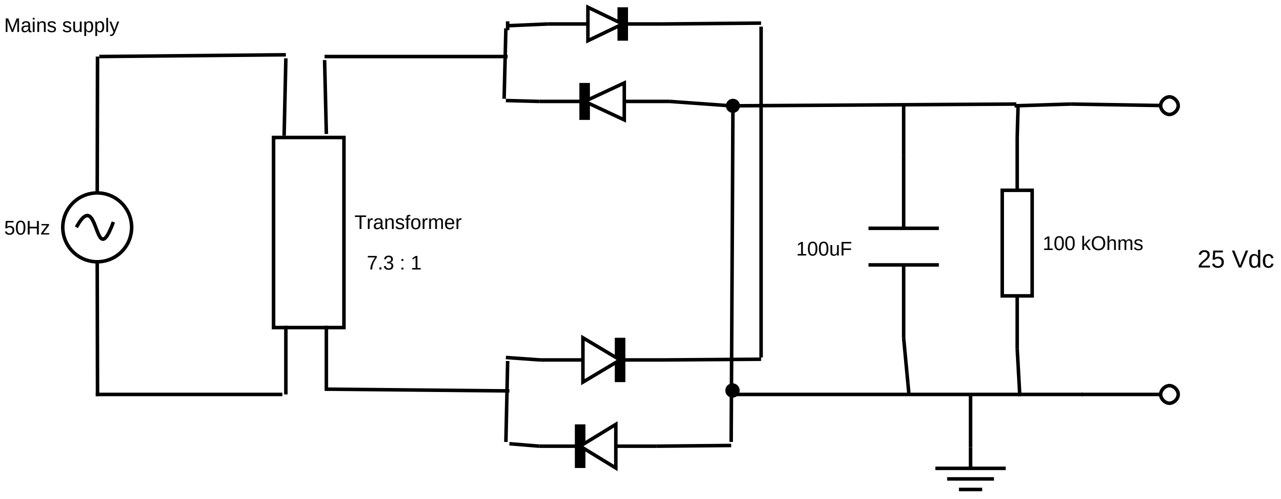


Figure 7: 28V supply signal circuit

[10]

3 Testing Procedure

The testing procedure was mainly divided in two parts, testing of the prime mover alone to determine its operating characteristics and then testing the prime mover driving the 400Hz generator. That is testing the system as a whole.

3.1 Testing the Prime mover - 15kW Induction motor

3.1.1 Introduction

To determine the characteristics of the induction motor, the no-load and blocked-rotor tests were carried out.These tests were used to determine the parameters of the equivalent circuit of the induction motor. The equivalent circuit is shown in figure 2. The induction motor used is a 15kW, three phase motor (for the motors specifications refer to table 2)

Equivalent circuit of an induction motor

The equivalent circuit for an induction motor, running at slip s, is used to predict the performance of the induction motor with reasonable accuracy. The parameters of the equivalent circuit R_C, X_M, R_1, X_1, $X_2$and R_2can be determined from the results obtained from the no-load test, a blocked-rotor test and from measurements of the dc resistance of the stator winding. The no-load test gives information on exciting current and rotational losses. The blocked-rotor test gives information on leakage impedance[1].

3.1.2 Testing Arrangement

The following equipment was used for the no-load and blocked-rotor test:

- a 3 phase variac
- 2 watt-meters,W
- a voltmeter,V
- an ammeter,A
- 2 current transformers,CT

The equipment was setup in the following way:

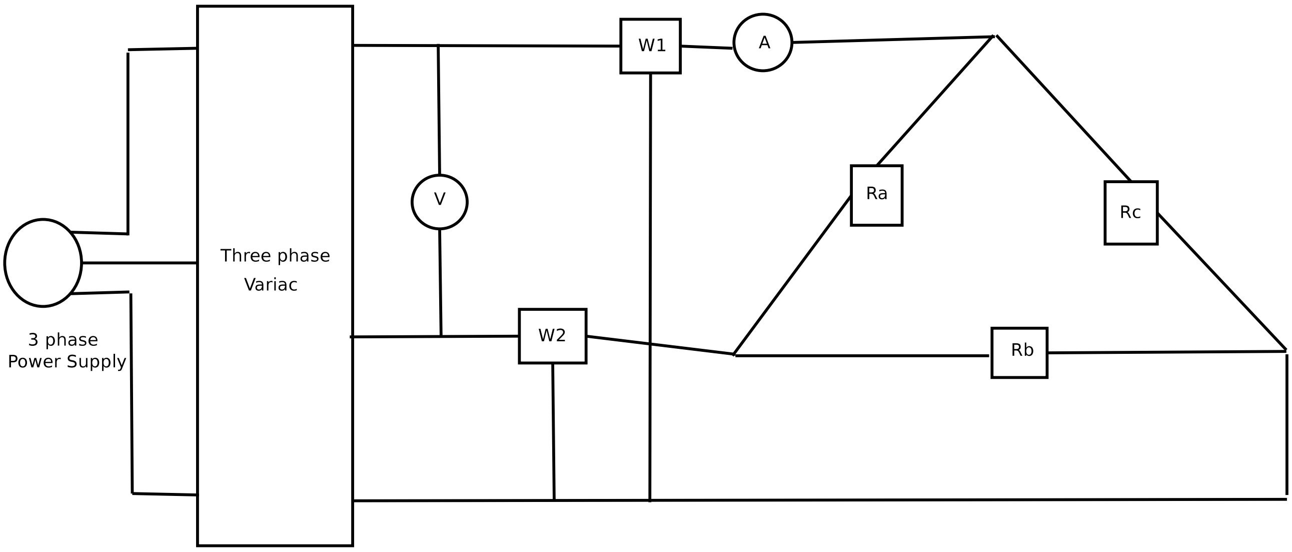


Figure 8: Equipment arrangement

The current transformers were used to step-down the current because the watt-meters can only take a maximum voltage of 5V while the rated current for the motor is 26.5A.

3.1.3 Determining of the Equivalent circuit parameters

The parameters of the equivalent circuit are determined from the results of a no-load test, a blocked-rotor test and from measurement of the dc resistance of the stator winding.

Determination of parameters under no-load conditions

The no-load test of an induction motor gives information about exciting current and rotational losses. The measured power under no-load conditions is dissipated across two components - R_C and R_1. The value of R_1 can be measured directly using a galvanometer and therefore the power loss across this component can be calculated. Because the branch resistance is much larger than the stator components, R_C is approximately equal to[11]:

$$R_C = \frac{E^2}{\text{Power dissipated across } R_C} \tag{4}$$

The remaining equivalent circuit (shown in figure 9) is used to determine the branch reactance X_M. Note here that because

X_M is not small enough to ignore, the stator resistance and reactance must be left in the circuit. Therefore, the combined reactance X_1+X_M is calculated using the reactive power component[11].

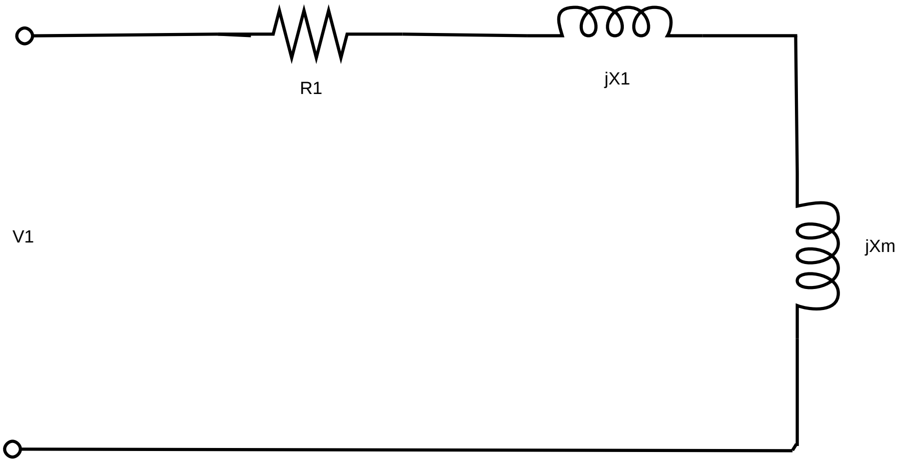


Figure 9: No-load equivalent circuit for an induction motor

Determination of parameters under blocked-rotor conditions

Because the currents in the stator are higher now, we can ignore the shunt parameters. This leaves the following equivalent circuit[11]:

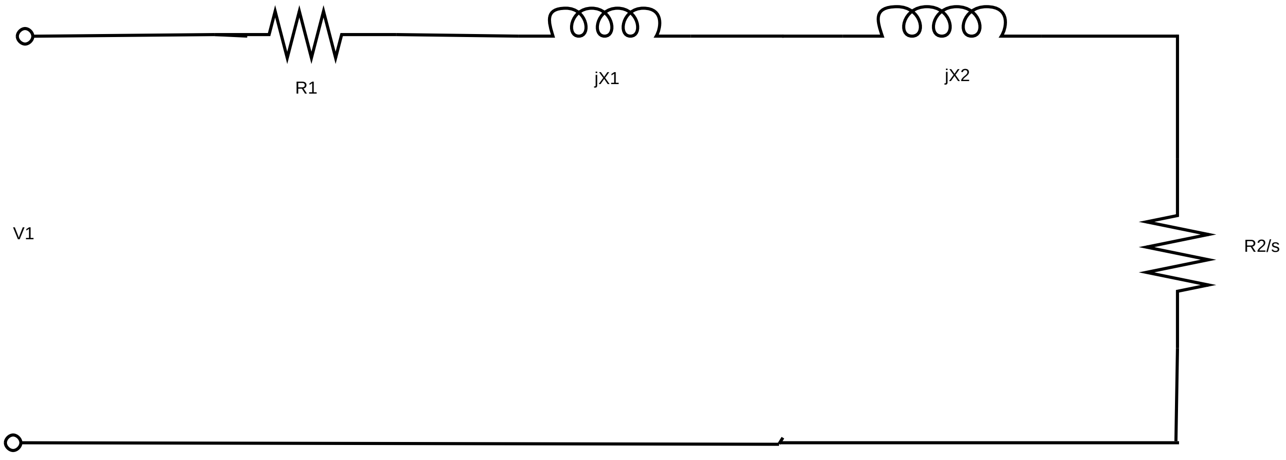


Figure 10: Blocked-rotor equivalent circuit for an induction motor

The measured power value were used to determine the rotor resistance and the reactive power calculated was used to determine the reactance. It is assumed that $X_1 = X_2$[11].

3.1.4 Experimental determination of the equivalent circuit parameters

1.No-Load Test

In this test there is no load exerted on the motor except its own windage and frictional losses. This means we can ignore the rotor components[11]. Refer to figure 9

Experimental Procedure

1. The 3 phase variac was set to zero and the power to the variac was switched on. The variac was adjusted to 400V and the following were measured:

Line current I_L = 9.5A

Line voltage V_L = 400V

Power_1 = -1200W Power_2 = 2100W

Total Power = Power No-Load = P_{NL} = 900W

These values are used to determine the phase, reactive and apparent power.

Phase power = $\frac{900}{3}$ = 300W

Phase apparent power = $\frac{\sqrt{3}V_L I_L}{3}$ = $\frac{\sqrt{3}\times 400\times 9.5}{3}$ = 2193.93VA

Phase reactive power = $\sqrt{2193.93^2 - 300^2}$= 2173.32VAR

2. The resistance of the 3 stator windings were measured using a galvanometer and the average resistance R1 was computed. Because of the delta configuration, the stator phase resistance are set up as shown below:

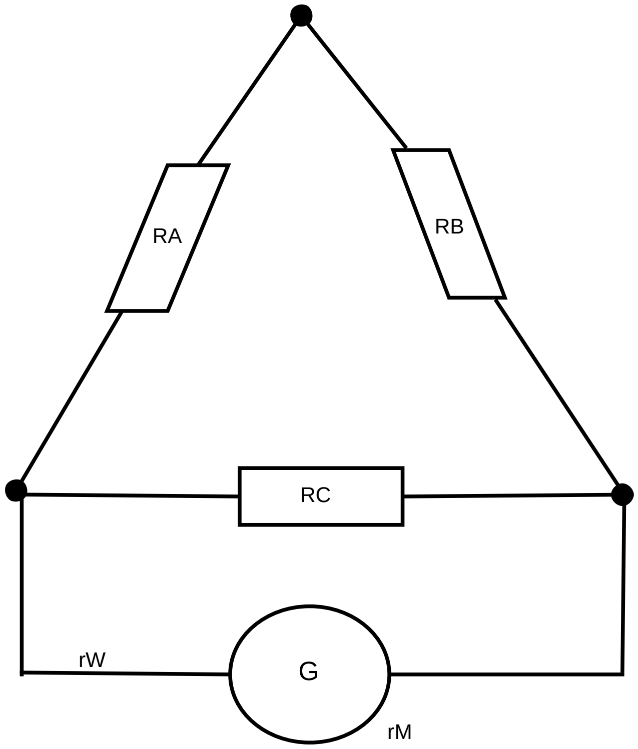


Figure 11: Delta connected resistance arrangement

where

r_M = measured resistance

r_W = resistance of wiring

R_A, R_B, R_C = per-phase stator resistance

The actual r_M = r_M - r_W

The measured values were:

r_{MA} = 0.548 Ohms r_{MB} = 0.553 Ohms r_{MC} = 0.558 Ohms

r_W = 0.014 Ohms

Hence the actual measured values were:

r_{MA} = 0.534 Ohms r_{MB} = 0.539 Ohms r_{MC} = 0.544 Ohms

The per-phase stator resistance, r_m is obtained by the following formula:

$$r_m = \frac{R \times 2R}{R + 2R} \tag{5}$$

hence r_{MA} = 0.534 Ohms will give

$$0.534 = \frac{R_A \times 2R_A}{R_A + 2R_A}$$

$$0.534 = \frac{2 \times R_A^2}{3}$$

R_A= 0.801 Ohms

and r_{MB}= 0.539 Ohms will give

$0.539 = \frac{2 \times R_B}{3}$

R_B= 0.8085 Ohms

and r_{MC} =0.544 Ohms will give

$0.544 = \frac{2 \times R_C}{3}$

R_C= 0.816 Ohms

The average resistance per stator phase is therefore

$R_{ave} = R_1 = \frac{R_A + R_B + R_C}{3}$

$R_1 = \frac{0.801 + 0.8085 + 0.816}{3}$

$R_1 = 0.8085$Ohms

Calculations of parameters

From the no-load test,

P_{NL} = 900W

$i_1 = \frac{9.5}{\sqrt{3}}$ = 5.48A

V_1 = 400V

We can use these values to calculate the shunt resistance value, R_C as well as X_1+X_M.

The no-load impedance, Z_{NL} is

$Z_{NL}= \frac{V_1}{i_1} = \frac{400}{5.48}$= 72.99 Ohms

The no-load resistance, R_{NL} is

$R_{NL}= \frac{P_{NL}}{3 \times i_1^2} = \frac{900}{3 \times 5.48^2}$= 9.99 Ohms

The no-load reactance, X_{NL} is

$X_{NL} =\sqrt{Z_{NL}^2 - R_{NL}^2}= \sqrt{72.99^2 - 9.99^2}$=72.30 Ohms

Thus $X_1 + X_M = X_{NL}$ =72.30 Ohms

and $R_C = \sqrt{\frac{V_1^2}{i_1^2}}=\sqrt{\frac{400^2}{5.48^2}}$=72.99 Ohms

2.Blocked-rotor Test

In this test the shunt part of the circuit can be ignored to determine the equivalent circuit components (Refer to figure 10).Lock the rotor with a clamp and slowly increase the voltage until rated line current was flowing. The following values were recorded.

Line current I_L = 25A

Line voltage V_L = 60V

$Power_1$ = -200W $Power_2$ = 1100W

Total Power = 900W

As before these values are used to determine the phase, reactive and apparent power.

Phase power = $\frac{\text{Total power}}{3} = \frac{900}{3}$ = 300W

Phase apparent power = $\frac{V_L \times I_L}{\sqrt{3}} = \frac{60 \times 25}{\sqrt{3}}$ = 866.03VA

Phase reactive power =$\sqrt{866.03^2 - 300^2}$ = 812.41VAR

Taking that P_{BL} =blocked-rotor power and

R_{BL}= Blocked-rotor resistance

then from the blocked-rotor test, the blocked-rotor resistance, R_{BL} is

$$R_{BL} = \frac{P_{BL}}{3 \times (I_L/\sqrt{3})^2}$$

$$R_{BL} = \frac{900}{3 \times (25^2/\sqrt{3})}$$

$R_{BL} = 1.44$Ohms

The blocked-rotor impedance, Z_{BL} is

$Z_{BL} = \frac{V_L}{(I_L/\sqrt{3})} = \frac{60}{14.43}$ = 4.16 Ohms

The blocked-rotor reactance, X_{BL} is

$X_{BL} =\sqrt{Z_{BL}^2 - R_{BL}^2}= \sqrt{4.16^2 - 1.44^2}$=3.90 Ohms

$X_{BL} = X_1 + X_2$(approximately)

hence $X_1 = X_2 = \frac{3.90}{2}$= 1.95 Ohms

The magnetising reactance, X_M is therefore

$X_M = X_{NL} - X_1$= 72.30 - 1.95 =70.35 Ohms

The per-phase rotor winding resistance, $R_2$is obtained from the equation

$R_2 = \left(\frac{X_2 + X_M}{X_M}\right)^2 \times R$ R is from the fact that $R_{BL}$is the sum of $R_1$and an equivalent R, which is the
resistance of R_2+ jX_2in parallel to X_M. Therefore:

R = R_{BL}- R_1= 1.44 - 0.8085 = 0.6315 Ohms

hence $R_2 = \left(\frac{1.95 + 70.35}{70.35}\right)^2 \times 0.6315$

R_2= 0.6670 Ohms

3.2 Unforeseen problems

3.2.1 Stabilising the generator set

Introduction

The coupling unit was constructed to provide a mechanical link between the 15kW induction and the 400Hz generator. The generator set arrangement is shown in figure 1. During the design, the contractors did not cater for the mounting pin on the generator (refer to figure 12). The mounting pin is the point where a stud or screw fitted into the generating set thus preventing the whole generator twisting as the prime mover rotated.

However, this arrangement was not catered for in the design of the coupling unit and therefore the coupling unit had to be adapted to include a stud or screw in its structure.

Procedure for removing coupling unit

In order to include a screw on the coupling unit, a hole had to be drilled on the unit where a screw would be placed. Before this could be done the coupling unit had to be removed carefully. Since there was no adequate information from the contractors on the removal of the coupling unit, a removal procedure was devised after studying the design diagram of the coupling unit obtained from the contractors (refer to figure 3). The removal procedure is explained in detail in section 3.2.2.

Alterations made to the coupling unit

1.Problem After the unit was successfully removed, a hole had to be drilled on the unit where the screw would be fitted. The position of the hole had to be in line with the mounting pin shown in figure 12.

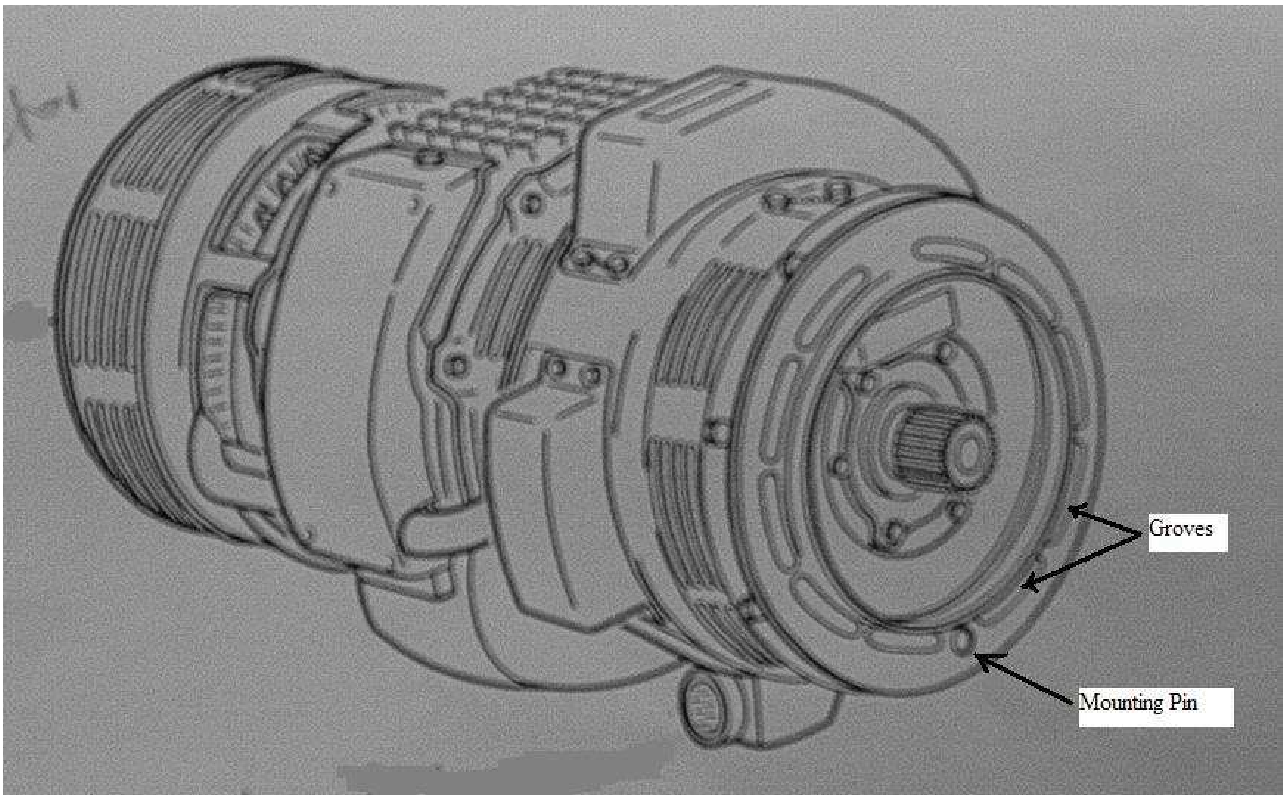


Figure 12: Position of mounting pin

[12]

After earmarking the position where the hole had to be drilled on the coupling unit. It was discovered that this point was not ideal. This was because of the way the coupling unit was constructed there was not enough steel (meat) to drill a hole in that position. Therefore, an alternative point had to be found were the screw would be fitted. Since there was only one mounting point on the generator we had to improvise.

Solution Though the generator had a single mounting pin, they are grooves around the generator shaft (refer to figure 12), which became useful. It was decided to fit to 2 screws at each end of the one grove (refer to figure 13) so that the screws would cater for twisting in either direction.

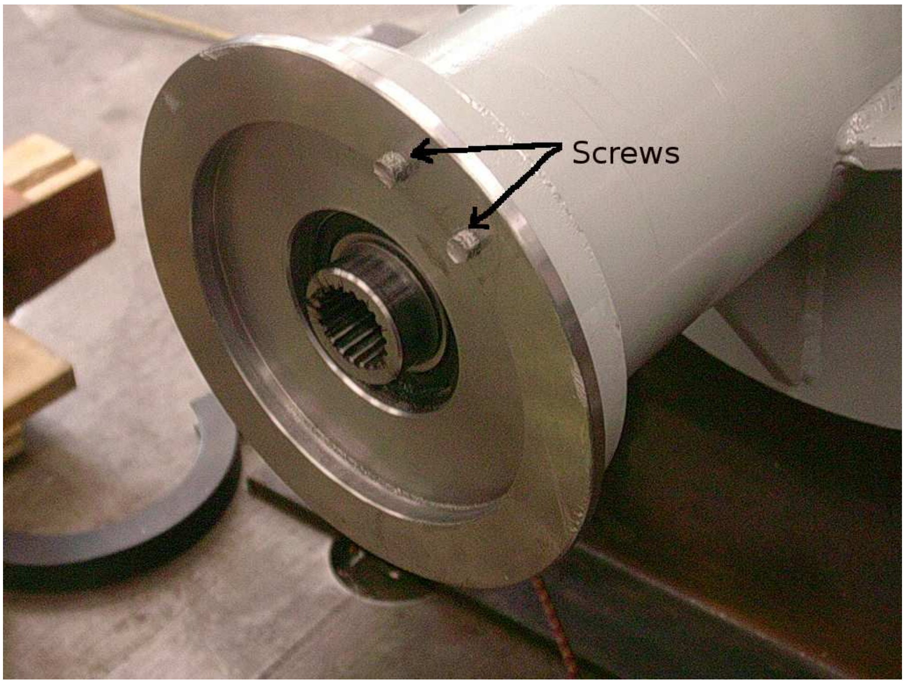


Figure 13: Position of screws

After the position of the screws on the coupling unit was determined, the holes were drilled in the electrical engineering workshop and the screws were fitted in place as shown above.

3.2.2 Removal of coupling unit

Since the construction of the coupling unit was regarded as a small project by the contractors (and they were nor betting on anyone wanting to remove the unit), the only information they had was the design diagram (refer to figure 3). After analysing of the diagram the following procedure was used to remove the coupling unit:

i. Remove the split lock ring between the generator and the coupling unit.

ii. Slid the generator out.

iii. Remove Allan key cover (refer to figure 14). There are two Allan key points 1 and 2. To remove the unit just concentrate on Allan key point 1 which has two Allan key points along the diameter of the jaw coupling.

iv. Remove all the Allan keys on Allan key point 1; this releases the induction motor shaft (shown in yellow in figure 14) attached to the jaw coupling.

v. Lastly slid the coupling unit carefully from the induction motor.

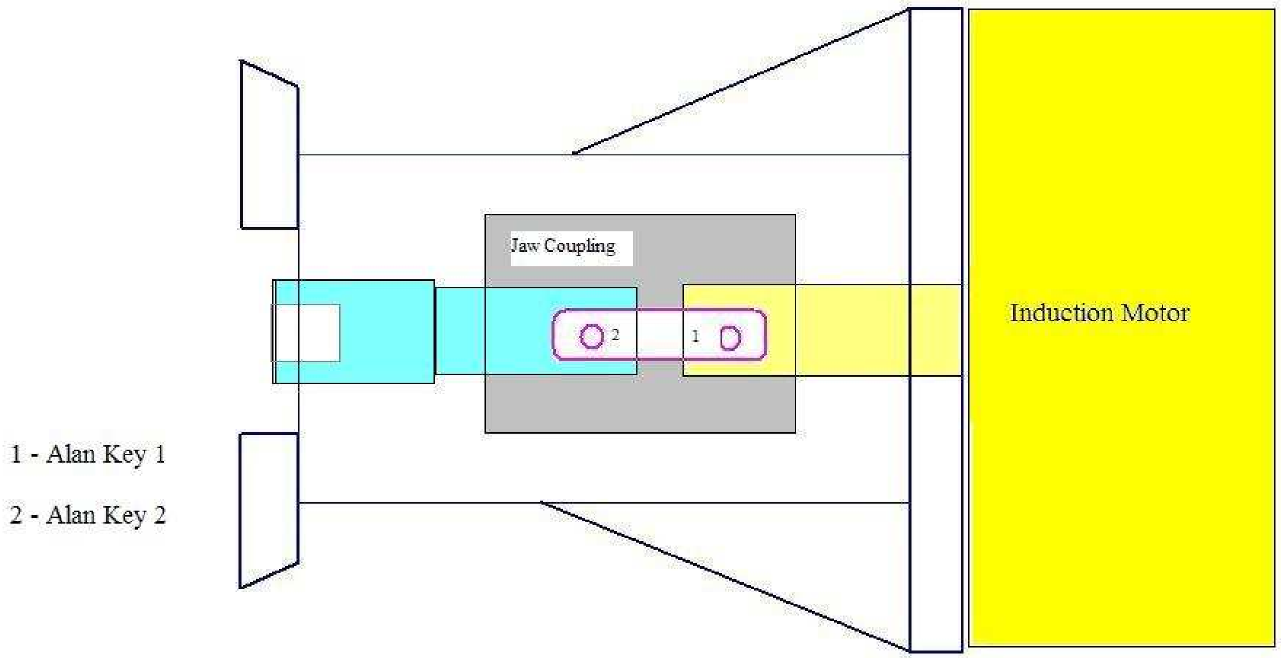


Figure 14: Detailed coupling unit diagram

Note: Allan key point 2 should not be tampered with because it is attached to the coupling unit sub shaft (shown in blue in figure 14) and has nothing to do with the removal of the unit.

3.2.3 Faulty connectors and wiring

After the stabilisation and removal issues were sorted, Leon was informed so that he would be present during the first test of the whole system. His expertise would be invaluable if the generator turned out to be faulty. That turned out to be the case, during the trail run serious wiring problems were picked up. The wiring of the generator was done as part of EEE 300X by undergrad students a few years back (see reference [10]). These problems can be divided into two:

1 Faulty wiring

The connectors on the 400Hz generator and regulator are special connectors, the 851 series produced by Souriau formerly used for military applications. These connectors have special crimp contacts that need a special tool to fit the contacts into place in the connector; neither the electrical or mechanical departments had the tools for the connector. Due to this limitation, the pins in the connector were not fitted right through the connector and therefore the regulator was not receiving the necessary 28V signal. The 28V signal supply is needed to turn on the relays. The turning on effect of the relays can be heard by a ”click” sound.

Solution

Though UCT did not have the necessary tools to fit the crimp contacts into the pin; a crude method was suggested that involves placing a very small screw driver at the rear end of the contact and literally forcing the contact in until a ”click” sound is heard. After the contacts were properly put into place, the regulator did turn on but the output values were still wrong.

2 Faulty Connector

Connector J1a on the regulator (refer to figure 20) was replaced by the undergrads who previously worked on this project (refer to reference [10]) in order to distinguish the two 19 pin male ports on the regulator. Hence, the male port on J1a was replaced with a female port but in so doing two pins were swapped around. This resulted in a tedious exercise of firstly disassembling the regulator box and then testing that the relevant circuit boards in the regulator had continuity with their corresponding pins on the connector J1a. After going through every pin and corresponding contact point on the circuit boards, the two pins where identified and corrected.

note: When doing this task, discrepancies between the circuit diagrams in the technical manual of the generator and the actual circuit were noticed. The circuit diagrams in the manual did not correspond fully with the circuits actually built in the regulator box.

3.2.4 Oil change

The reason for the oil change was the following; the 400Hz generator had been sitting ideal for a long time since it was obtained from the Mirage F1 plane. It would not have been wise to rely on the same oil in the generator for lubrication. Another important reason was that during the first test of the whole system, the generator overheated. With these reasons the probability of the oil having deteriorated or oxidised was very high. Hence a refill was carried out.

Oil used

Three types of Jet oil were recommended and are listed:

Table 4: Types of Oil

Description	Air	NATO
Turbo Nycoil 13B	3514	0150
Mobil Jet II	3514	0156
ESCO 2380	3514	0156

Caution: None of these oils are miscible[13]

The oil that was readily available was Mobil Jet Oil II, which has the following key features and benefits:

Table 5: Features and Benefits

Features	Advantages and Potential Be
Excellent thermal and oxidation stability	Reduces the formation of carbon and s
Excellent wear and corrosion protection	Extends gear and bearing life Reduces en
Retains viscosity and film strength across wide temperature range	Provides effective lubrication at high opera
Chemically stable	Reduces evaporation losses and lowers
Low pour point	Eases start-up in low ambient temperat

[14]

The Mobil Jet Oil II has the following typical properties:

Viscosity

cST @ 40^0C (120^0F) 27.6

cST @ 100^0C (212^0F) 5.1

cST @-40^0C (40^0F) % 11,000-0.15

change @ -40 C after 72 hours

Pour Point, ^{0}C(^{0}F), -59 (-74)

ASTM D 97

Flash Point, ^{0}C(^{0}F), 270 (518)

ASTM D 92

Fire Point, ^{0}C(^{0}F), 285 (545)

Autogenous Ignition, ^{0}C(^{0}F), 404 (760)

TAN (mg KOH/g sample) 0.03

Density @15^0C kg/l, 1.0035

ASMT D 4052

Evaporation Loss, % 6.5 3.0, 10.9, 33.7

hr@204 C, 29.5” Hg 6.5

hr@232 C, 29.5” Hg 6.5

hr@232 C, 5.5” Hg

(Equals pressure @ 40 000 Ft. altitude)

Sonic Shear Stability, KV 0.9 @ 40 C, change, %[14]

Oil draining and filling

The oil unit is located on the centre section,with two plugs used for oil filling and draining. In the documentation of the 400Hz generator, the following equipment was listed for use during this procedure:

Special tools:

- Drive wrench (spanner)

- Either :

  - a syringe pump equipped with a supply end-fitting.

  - a scavenge end-fitting equipped with a clear plastic pipe with one end in a pan.

- or:

  - a pressurised fluid feed unit equipped with filling adapter

  - a supply adapter

  - a scavenge end-fitting equipped with a clear plastic pipe [1]

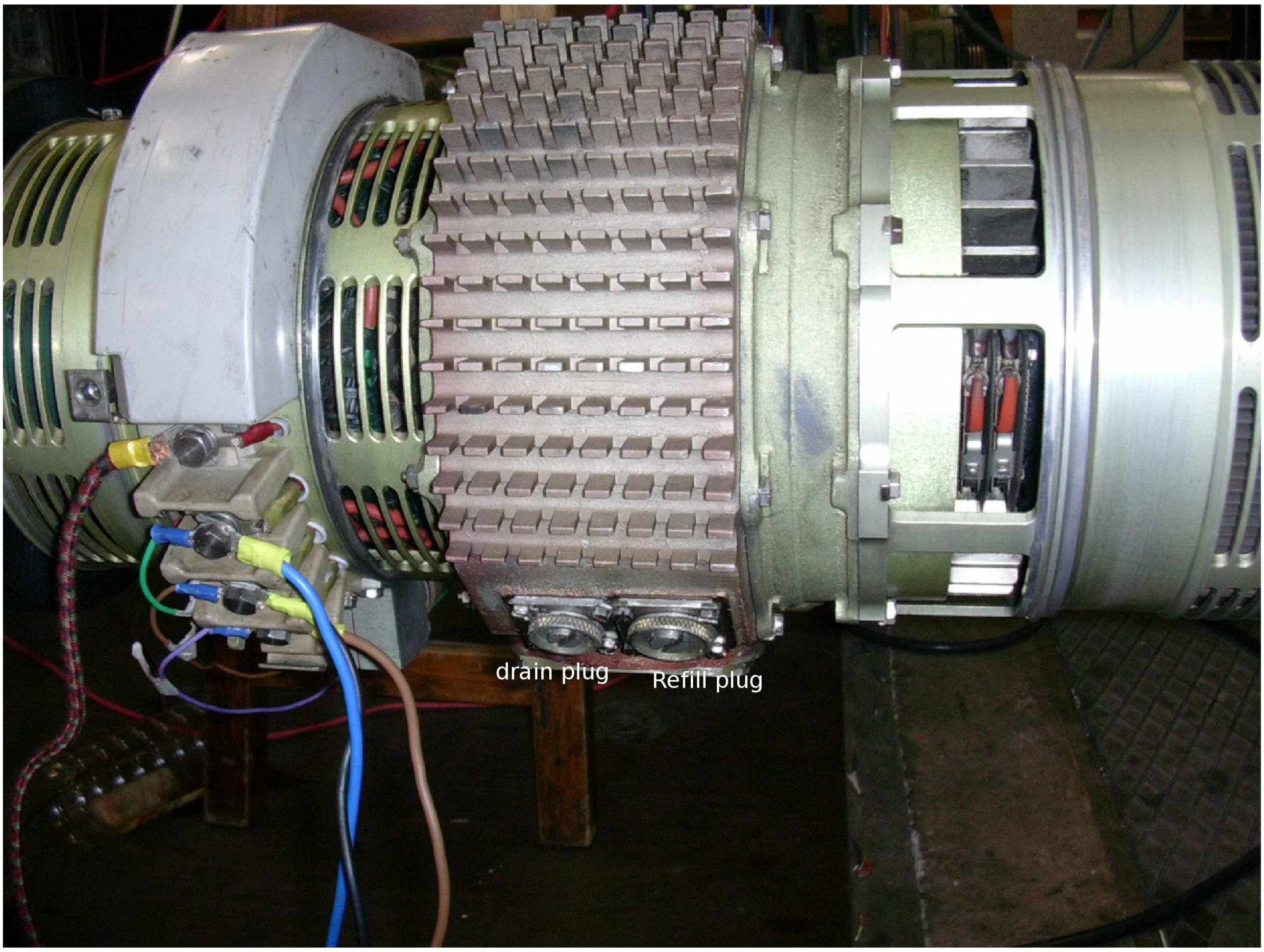


Figure 15: Oil unit

Neither the electrical nor the mechanical departments had any of the special tools mentioned above (except the spanner). It was therefore decided upon to use a syringe with silicon tubing fitted tightly to the syringe for refilling the generator. The size of the silicon tubing was big enough to fit tightly to the filler port. Since the refill plug has a valve, considerable pressure needs to be applied in order to force the oil in to the generator. Refer to figure 16 on the syringe used.

Figure 16: Syringe with oil container

Draining procedure

Note: Since the above tools were not available, the draining procedure followed compensated for this. But if proper tools are acquired it would be best to follow the method described in the documentation for the generator under section 9.

i. Unscrew drain overflow plug (refer to figure 15)

ii. Remove the four screws attaching draining body.

Note: As soon as draining body is removed, oil starts flowing out.

Note: When the oil stops flowing, install the draining body making sure to position it in its initial orientation.

iii. Place the attaching screws

iv. Tighten the screws

v. Install the plug

3.2.5 Cooling problem

After carrying out the first test on the generator, though it was seemed to be producing 400Hz and a voltage of about 200V, a concern was raised on the generator's temperature. From the generator's characteristics, the operating temperature range is between -25^{0}C and 80^{0}C. Because of the over-heating observed during the first test it was important to do a temperature analysis on the generator and determine how hot the generator becomes.

The temperature analysis tests were divided into two categories. The first tests involved running the generator with a specified load without using any cooling mechanism. The second tests involved using the same load but this time employing some out of cooling mechanism. A 504W duct fan was the only equipment available in the lab to act as a cooling mechanism. The equipment arrangement for these tests is shown in figure 17.

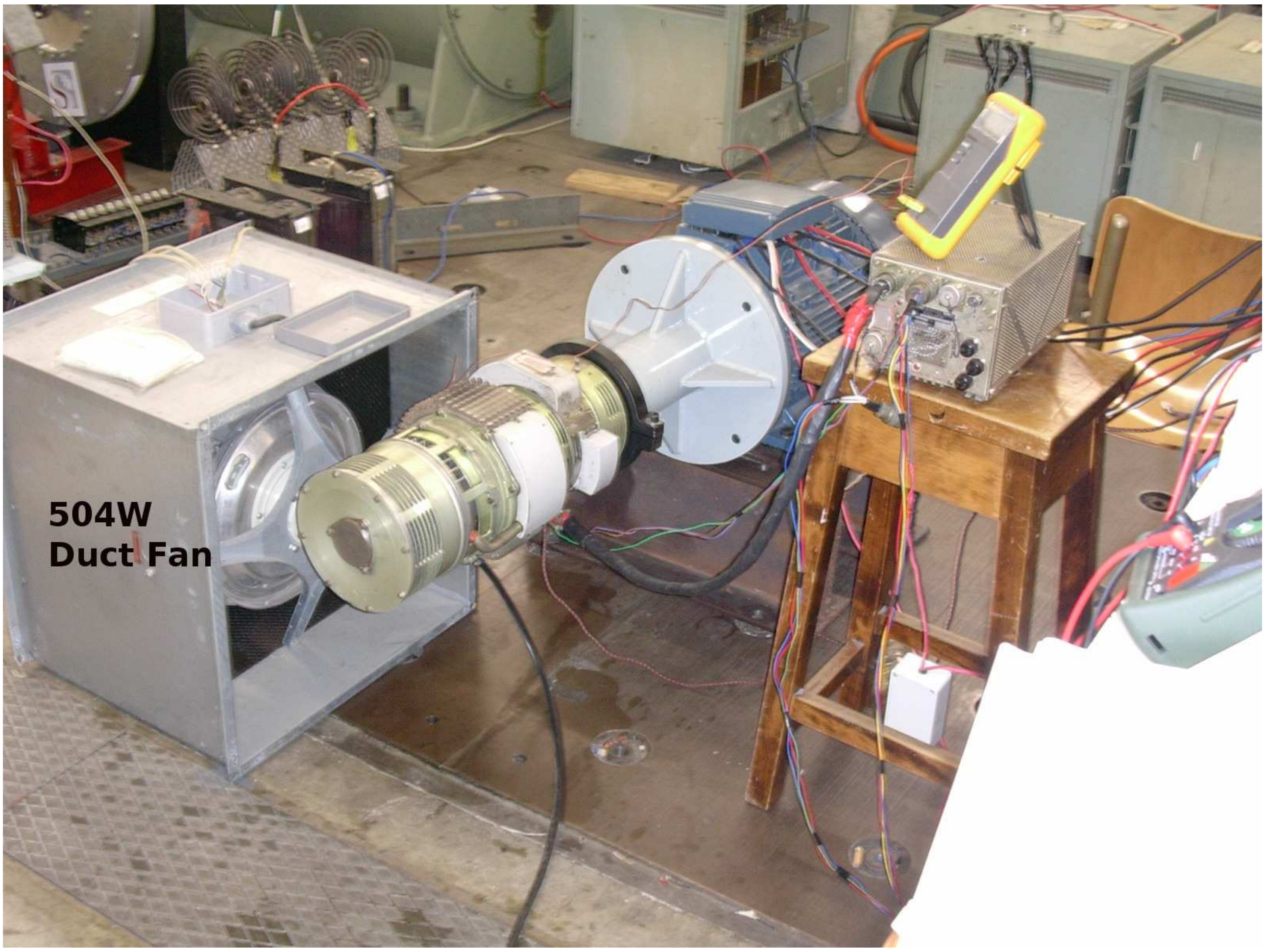


Figure 17: Generator set with fan

1 Tests without cooling fan

These tests were done with a 1 kW load. The temperature was measured by placing the thermometer on the heat sink on the generator. These were the results obtained are represented by the figure 18 below.

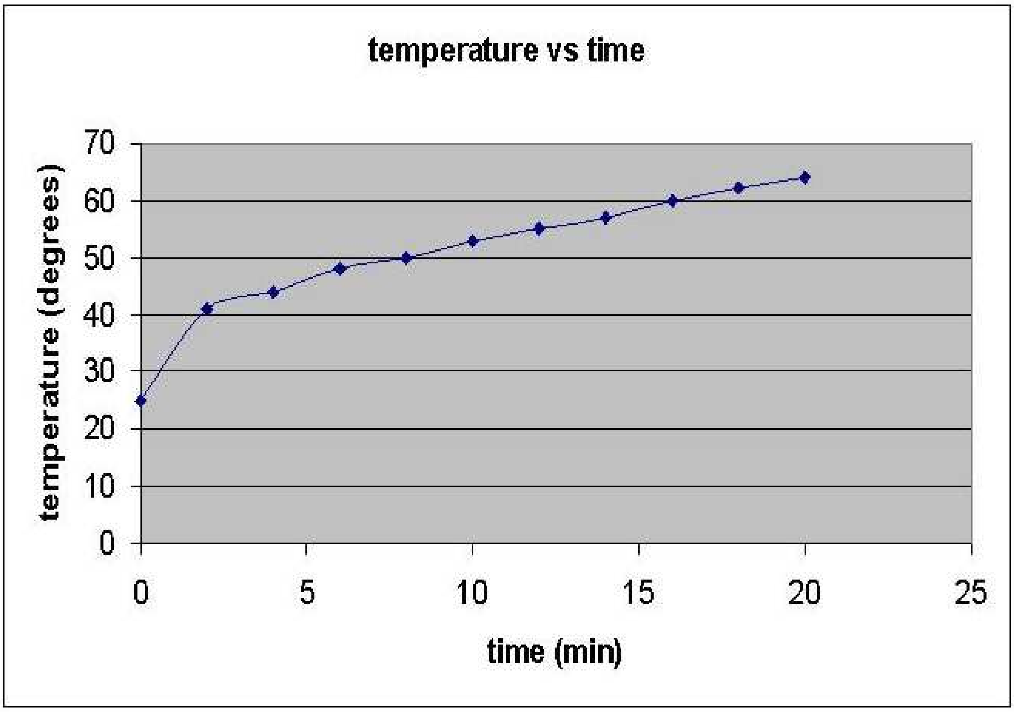


Figure 18: Temperature readings without cooling

2 Tests with the cooling system

These tests involved the same 1 kW load. The same thermal tests were carried out and the results obtained are represented below with the graph.

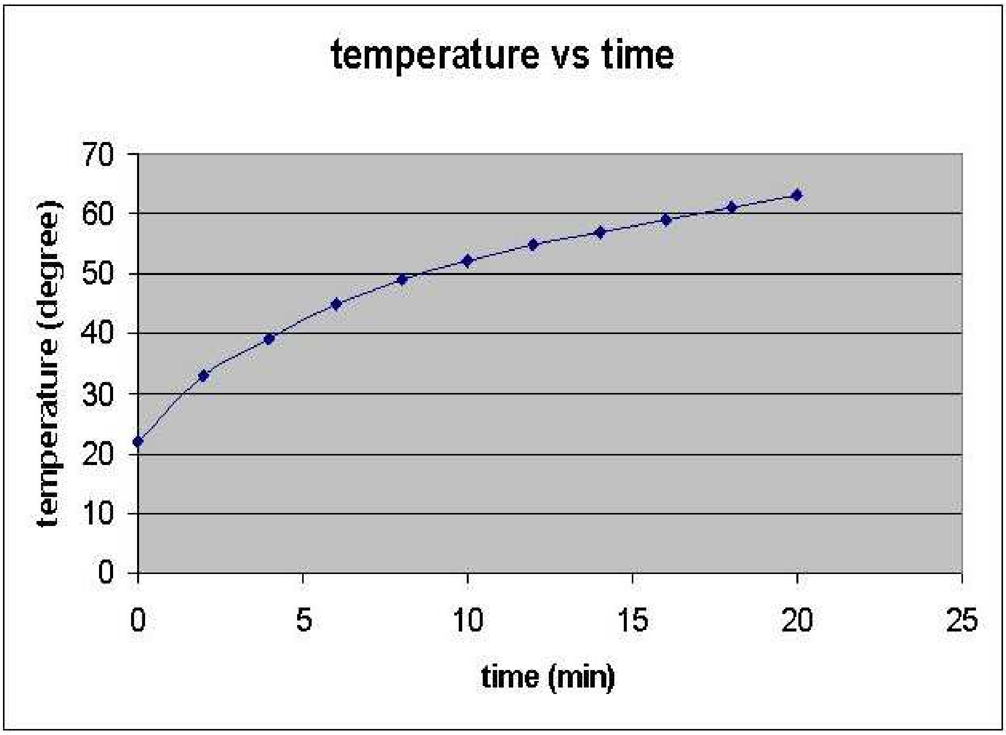


Figure 19: Temperature readings with cooling

3 Analysis of the results obtained

From the two graphs it can be seen that the duct fan has no real effect on the temperature of the generator. The generator needs to be force cooled at 3000 Pa for the cooling to be effective.The best option at the moment was to run the generator for less than 20 minutes during testing procedures and then giving it time to cool down, 30 minutes. Therefore, in the implementation phase a cooling mechanism has been designed that will ensure that the generator receives the right pressure for cooling (refer to section 5.2).

3.2.6 Faulty Electro-mechanical drive system

After these clear issues had been dealt with, the major problem with the generator was noticed. Ideally, the outputs of the 400Hz power supply would be a voltage of 200V ± 2% and a frequency of 400Hz ± 1%. In this case the generator seemed to be ”hunting” for the correct speed to produce 400Hz. The control of the speed of the generator is done by the electro-mechanical; something was causing it to malfunction. To put this more clearly, the generator did not fix on the correct output values; it locked on the output values for a few seconds and then it would lose the values momentarily, and then lock again on the correct values.

According to the operation of the generator, the generator is supposed to consistently produce 200V ± 2% and 400Hz ± 1%. The fault finding procedure followed was as described below:

1 Re-checking the system wiring

Faulty wiring and connections was one of the earlier unexpected issues. Though the wiring had been checked before, the current wiring job did not inspire any confidence. Hence the first task done was re-checking the wiring for continuity. After this was done and no problem was found the grounding of the generator was checked.

2 Grounding of the 400Hz generator

The grounding diagram (Figure 58 in the Technical manual of the generator) highlighted some differences with that of the actual grounding connections of the generator. In the diagram, the regulator box is grounded through a pin on connector J2b; and the pin was physically connected to the earth of the 400Hz generator through a wire. In the actual setup, the regulator was grounded through the 28V signal supply’s earth. There was no physical connection between the ground on the generator and that of the regulator box. When tested, the two grounds were at different potentials. This was solved by running a wire between the generator and the regulator box (refer to figure 20 for generator setup). However, though the grounding of the power supply was sorted, the hunting problem was still occurring.

3 Checking the resistor values

The complete technical manual of the generator was not available at the time therefore it was impossible to find out the actual resistor values across the generator. A possible reason of the malfunction could have been that a component either in the generator or the regulator had been damaged hence hampering the control mechanism of the generator. Such a problem could have been detected by checking for discrepancies with the resistor values.

Regardless of this limitation, consistence of the resistor values across the connector on the generator with those across the testing points (J3 and J5) on the regulator was checked. The logic behind this was, taking the values across the connector on the generator as the real values and then checking if these corresponded with those across the testing points on the regulator. If the values differed then the problem lay with the regulator but if the values corresponded then the problem lay in the generator. The resistance values obtained are shown in table 6below:

Table 6: Resistance values

Parameter	Generator connector		Regulator test points
	Pin	Value	Value
Clutch inductor	E and GND	165 Ohms	25.11 k Ohms
	F and GND	34 Ohms	64.2 k Ohms
Permanent magnet generator	T and H	1.3 Ohms	100 k Ohms
	H and G	1.3 ohms	100 k Ohms
Exciter inductor	P and R	28 Ohms	59.2 k Ohms

The resistor values across the connector appeared to be more realistic than those across the test points on the regulator. These results seemed to show that the regulator was faulty. At this stage Leon was contacted and another similar 400 Hz generator was brought along. The other 400Hz generator was setup under the same conditions so as to finally deal with the problem.

4 Comparing the two generators

First of all the overheating issue was re-checked trying to make sure that the heating experienced was the natural reaction without any proper cooling available. This was found to be the case because the other generator got as hot as the previous generator. This process further confirmed that the generator needed to be force cooled.

When the resistors were checked, it appeared that the regulator was faulty; in actual fact, it was discovered that the where discrepancies in the actual technical documentation of the 400Hz generator. After the regulator had been disassembled , it was discovered that the test points on the actual regulator were not connected at the same points as described in the documentation. Note that these are just test points and therefore the positioning does not affect the operation of the regulator. Because of this discovery, the comparison of the resistor values proved to be a useless exercise.

The break through came after the other generator with all its components connected similar to that of the 400Hz generator surprising showed the same results, it was also ”hunting”. The chances that two separate 400Hz generator had the same faults was very low. Therefore, this problem was not likely due to a fault but probably due to the setup of the equipment. The first setup problem suggested was the use of the variable speed drive as a starter mechanism. It was suggested by Leon that the variable speed drive was trying to regulate the input speed while the electro-mecahical speed drive was also trying to do the same. This brought about the ”hunting” behaviour because of a scenario where the electro-mechanical speed drive is chasing after the regulated speed from the variable speed drive. It was then suggested to use a star/delta starter instead of the variable speed drive so that we have the ideal situation where the speed control is only done by the electro-mechanical speed drive.

But before this was done, it was decided to add the frequency limiting resistors into the setup just to see what effect this might have. The limiting resistors where added by simply connecting connector J4d on the regulator (refer to figure 20). The frequency limiting resistors had been left out of the set up (J4d was disconnected) because the only come in when the frequency change is to fast. The come in to apply more breaking. It was suggested by Leon at the beginning of testing that the frequency limiting resistors would not be useful because we are running at a constant speed of 2940 rpm. The generator uses three methods of speed control, the main method is the clutch mechanism but this is supported by the eddy current braking system and frequency limiting resistors which come in if the speed change is to fast. The frequency limiting resistors work by applying a 3 kW load on the generator to act as additional braking when the frequency change is too fast. Surprisingly, the addition of the frequency limiting resistors dealt with the ”hunting” problem; this meant that the arrangement of a variable speed drive and the electro-mechanical drive system resulted in fast frequency changes.

After the ”hunting” problem was finally dealt with and the 400Hz generator was now producing the desired output of 200V ±2% and 400Hz±1% , load tests on the generator where carried out (refer to section 3.3).

3.3 Testing the whole generator

3.3.1 Introduction

The major part of this project was testing the performance of the constant frequency generator. This meant putting the system together in the lab, that is the adjusting unit and the regulator with their corresponding wiring where connected to the 400Hz generator. Before this the wiring available was checked for continuity and the problems with the wiring harness were dealt with.

After the components were connected, the generator was run through the tests to gauge its performance. These tests were the following:

- Testing if the regulator is producing ± 2% of the output voltage that is 200V or 115V and also whether the output frequency is within the ± 1% of 400Hz. This turned out to be a big problem in which the generator was ”hunting” but this issue was sorted hence this section describes the load testing done.
- Testing the response of the generator to different amounts of load then gathering the 400Hz generator’s efficiency at these loads and also the maximum loading on the generator.

These tests where carried out to determine the stability of the physical system.

3.3.2 Equipment arrangement

The 400Hz power supply was connected as shown in figure 20 to the regulator, adjusting unit and the 28 V signal unit.

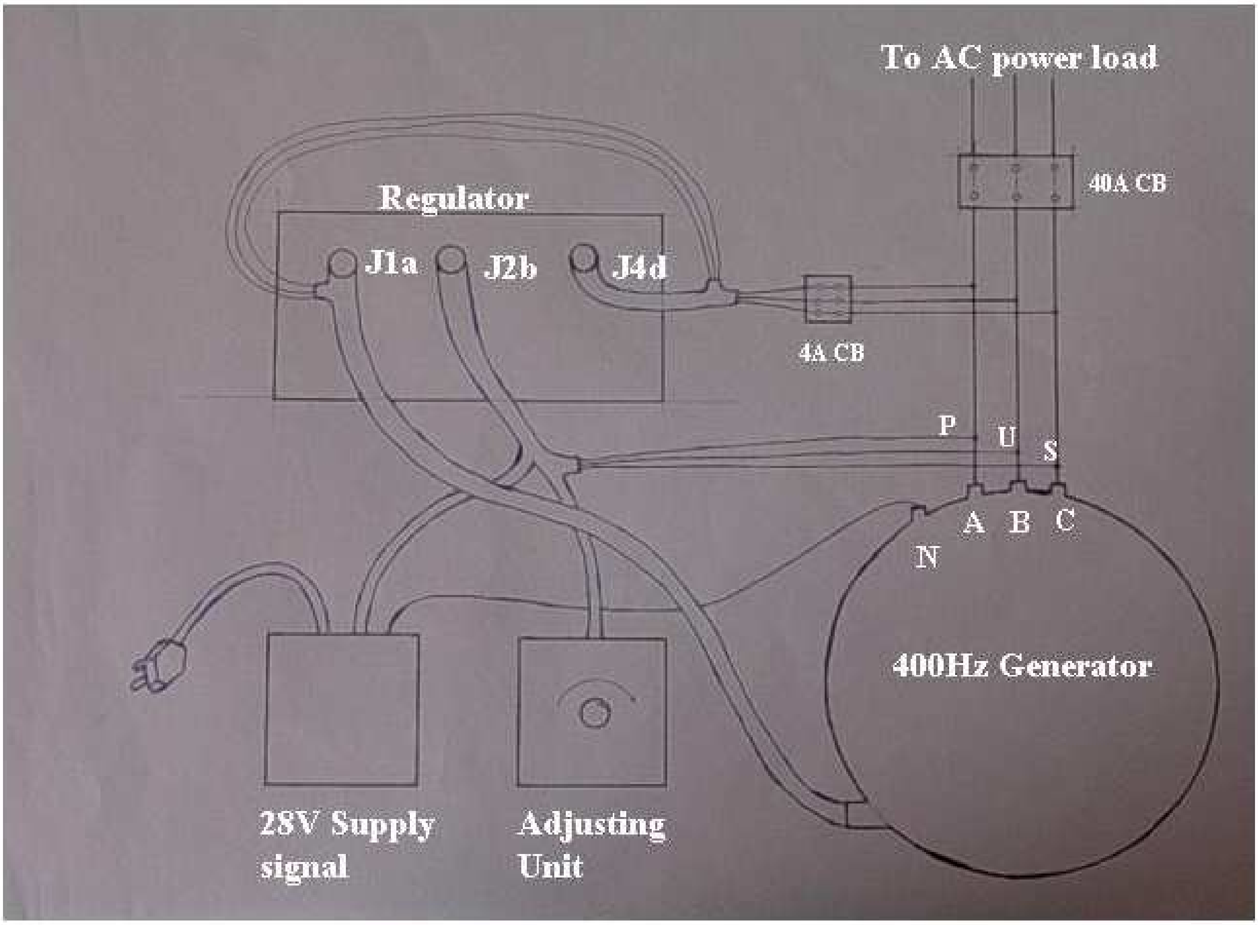


Figure 20: System arrangement

3.3.3 Load tests

When carrying out the load tests, it was noted the 400Hz generator was working properly because the frequency limiting resistors where added to the setup. This meant that on top of the load we were applying on the generator there was also the 3 kW load from the frequency limiting resistors that has to be added in order to get the true load value applied on the generator. The results obtained are tabulated below.

Operating conditions:

- Supply voltage = 218V
- Room temperature = 25^{0}C
- Supply frequency = 50.2 Hz
- Load connection = delta

Description of parameters in table:

- i_{in}= supply current
- P_1= power value from watt meter,W1 []
- P_2= power value from watt meter,W2 []
- P_{in}= Total input power that is P_1+ P_2
- V_{line}= applied load line voltage
- i_1,i_2, i_3= applied load line current
- $i_{line} = \frac{i_1+i_2+i_3}{3}$
- P_{line}= applied load power
- P_{out}= P_{line}+ 3000 W
- $Eff = \frac{P_{out}}{P_{in}} \times 100$ note: This efficiency value is the efficiency of the whole system
- F = frequency

Table 7: Loading Results

i_{in}(A)	P_1(W)	P_2(W)	P_{in}(W)	V_{line}(V)	i_1(A)	i_2(A)	i_3(A)	i_{line}(A)	P_{line}(W)	P_{out}(W)	Eff (
12.5	4800	600	5400	201	4.93	4.95	4.94	4.94	1720	4720	87
13.0	5000	800	5800	201	5.88	5.95	5.80	5.87	2044	5044	87
14.5	5800	1800	7600	201	9.35	9.44	9.20	9.33	3248	6248	82
17.0	6500	2600	9100	201	12.67	12.85	12.56	12.69	4418	7418	82
21.0	8300	4500	12800	201	19.30	19.75	18.88	19.31	6723	9723	76

4 Results and Analysis

4.1 15kW induction motor

4.1.1 Results of tests

The no-load and blocked rotor tests in chapter 3 were used to determine the equivalent circuit parameters of the induction motor. These parameters calculated in chapter 3 will be used to determine the performance characteristics of the motor in this section. The performance characteristics calculated will be compared with the real values obtained from the manufacturer's data sheets (refer to table 2). These tests were done in order to have a better understanding of the performance of the 15kW induction motor at its rated value.

From the calculations of the equivalent circuit parameters in section 3.1; the per phase parameters can be summarised as follows:

R_1= 0.8085 Ohms
R_2= 0.6670 Ohms
X_1= X_2= 1.95 Ohms
X_M= 70.35 Ohms

The rotational losses,P_{rot} are given by the formula:

$P_{rot} = P_{NL} - (3 \times i_1 \times R_1) = 900 - (3 \times 5.48^2 \times 0.8085) = 827$W

The performance characteristics in the steady state are the efficiency,power factor,current, rated torque, slip and starting current. The calculation of these devices is shown below.

1 Rated torque

The torque on the shaft can be determined from the equation:

$$T = 9.55\frac{P_r}{n_s} \quad \text{where}$$

$$P_r = 3 \times \frac{\frac{400^2 R_2}{\left(R_1^2+4X_1^2\right)}}{s^2 + \frac{2R_1R_2s}{\left(R_1^2+4X_1^2\right)} + \frac{R_2^2}{\left(R_1^2+4X_1^2\right)}}$$

$$P_r = 3 \times \frac{134.55}{0.0004 + 0.00136 + 0.028}$$

$$P_r = 13543.25W$$

$$T = 9.55 \times \frac{13543.25}{3000}$$

$$T = 43\,Nm$$

2 Internal efficiency and motor efficiency at full load

Air gap power:

$P_{ag} = T \times w_n = 49 \times 314.16 = 15393.8$W

note: P_{ag}represents the power that crosses the air gap between the stator and rotor and thus includes the rotor copper loss as well as the mechanical power developed.

Rotor copper loss:

$P_{rotor} = s \times P_{ag} = 0.02 \times 15393.8 = 307.8$W

Mechanical power:

$P_{mechanical} = (1 - s) \times P_{ag} = (1 - 0.02) \times 15393.8 = 15085.9$W

Output power:

$P_{out} = P_{mechanical} - P_{rotor} = 15085.9 - 307.8 = 14778.1$W

Input power:

$P_{in} = 3 \times V_1 \times i_1 \times \cos\theta = 3 \times 400 \times \left(\frac{26.5}{\sqrt{3}}\right) \times 0.90 = 16523.76$W

Motor efficiency:

$Eff_{motor} = \frac{P_{out}}{P_{in}} = \frac{14778.1}{16523.76} = 0.894 = 89.4\%$

Internal efficiency:

$Eff_{internal} = (1 - s) = 1 - 0.02 = 0.98 = 98\%$

3 Rated slip

$$s = \frac{n_S - n}{n_s}$$

$$s = \frac{3000 - 2940}{3000} = 0.02$$

4 Starting current

At start up, s=1 hence from figure....., the input impedance is:

$$Z_1 = R_1 + jX_1 + X_M \parallel \left(\frac{R_2}{S} + jX_2\right)$$

$$Z_1 = R_1 + jX_1 + X_M \parallel Z_2$$

$$Z_1 = R_1 + jX_1 + \left(\frac{jX_M\left(\frac{R_2}{S}+jX_2\right)}{\frac{R_2}{S}+j(X_2+X_M)}\right)$$

$$Z_1 = 0.8085 + j1.95 + \left(\frac{j70.35(0.6670+j1.95)}{0.6670+j72.3}\right)$$

$$Z_1 = 0.8085 + j1.95 + 0.635 + j1.902$$

$$Z_1 = 1.4435 + j3.852$$

$$Z_1 = 4.113\angle 69.46\text{Ohms}$$

$$I_{st} = \frac{400\sqrt{3}}{4.113\angle 69.46} = 168.44\angle -69.46^0\text{A}$$

5 Rated current

$$\frac{R_2}{s} = 33.35\text{Ohms}$$

$$Z_1 = 0.8085 + j1.95 + \left(\frac{j70.35(33.35+j1.95)}{33.35+j72.3}\right)$$

$$Z_1 = 0.8085 + j1.95 + 26.04 + j13.91$$

$$Z_1 = 26.84 + j15.86$$

$$Z_1 = 31\angle 30.56\text{Ohms}$$

$$i_{rated} = \frac{400\sqrt{3}}{31\angle 30.56} = 22.35\angle -30.56^0\text{A}$$

6 Power factor

$$PF = \cos(30.56) = 0.86\text{(lagging)}$$

4.1.2 Analysis of results

The analysis of the calculated performance characteristics is a comparison of the calculated values and those obtained from the manufacturers data sheets. The calculated values and the real values are shown in table 8 below for comparison.

Table 8: Comparison of characteristic values

Parameter	Real value	Calculated value	Units
Efficiency	90.0	89.4	%
Starting current	174.9	168.44	A
Rated torque	49	43	Nm
Power factor	0.90	0.86	
Rated current	26.5	22.35	A
slip		0.02	

The error in the results are caused by using analog measuring devices and most importantly, it is stated that the equivalent circuit parameters do not give you the actual values but reasonable estimates of those values (refer to p.222 of reference [1]).

4.2 400Hz power supply

4.2.1 Results of tests

The most important results of the load testing is the efficiency of the power supply system. The efficiency values are summarised in table 9 below with their corresponding load values. Note that the actual loading of the generator started at 4800 W because the smallest load of 1800 W had to be added to the load of 3000 W from the frequency limiting resistors already present on the generator.

Table 9: Efficiency of the Power Supply

Power in	Power out	Efficiency
5400	4740	87 %
5800	5044	87 %
7600	6248	82 %
9100	7410	82 %
12800	9723	76 %

4.2.2 Analysis of results

The load of 9723 W caused an overload in the circuit which shows that the generator can be loaded safely up to 7410 W but a load of 9723 W is too much. This is because at the rated speed of 2940 rpm for the induction motor, the rated output power of the generator is 12 k VA with a power factor between 0.75 lagging to 1. taking the worst case scenario of a power factor of 0.75, the maximum real output power of the generator is 12 k VA $\times 0.75$ = 9 kW. Since the 9723 W load caused an overload, the power factor of the generator is about 0.75. The efficiency at a load of 7410 W is 82 % which is still reasonable but above that the efficiency drops below 80 % and also you are reaching around the maximum load of the generator. The load range was limited due to the addition of the frequency limiting resistors but it appears that at loads less than 4740 W the efficiency could be better.

The limitation was brought about by the frequency limiting resistors, which apply a permanent 3000 W load on the output in order to stabilise the 400Hz power supply. The use of the variable speed drive could have lead to this problem, before commissioning the star/delta starter must be tested without applying the frequency limiting resistors. This could eliminate the use of the frequency limiting resistors and therefore loads less than 3000 W could be applied which would increase the efficiency of the 400Hz power supply.

5 Implementation design

This project will lead to the eventual commissioning of the 400Hz supply system. This will involve adding the star/delta starter system already installed on level six to the system. For safety precautions circuit breakers need to be added. An emergency switch is available on the panel housing the star/delta starter system for remote starting of the system.

5.1 Starter mechanism - Star/Delta starter

5.1.1 Introduction

A.C Induction motors are traditionally started and stopped by applying and removing the A.C supply. In many situations, the start current (5 to 6 times the rated current) must be reduced because this can cause a disturbance on the supply line or this may cause a problem with the driven load.Therefore a reduced voltage starter such as a star/delta starter is employed [2].

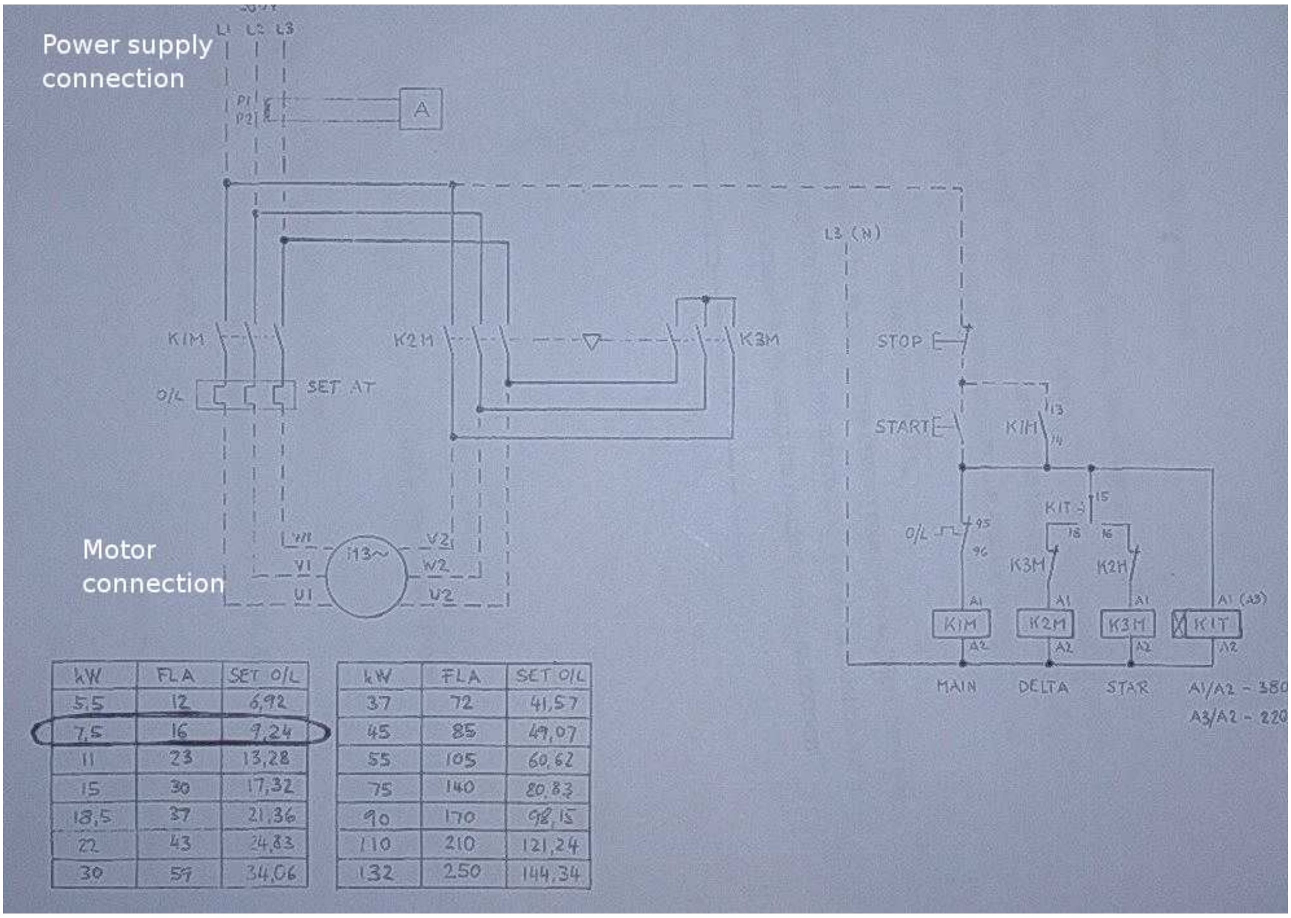
5.1.2 Star/Delta starters

The Star/Delta starter can only be used with a motor which is rated for connection in delta operation at the required line voltage which this motor is, and has both ends each of the three windings available individually. At Start, the line voltage is applied to one end of each of the three windings, with the other end bridged together, effectively connecting the windings in a star connection. Under this connection, the voltage across each winding is $1/(\sqrt{3})$ of line voltage and so the current flowing in each winding is also reduced by this amount. The resultant current flowing from the supply is reduced by a factor of 1/3 as is the torque[2].

When the on button is pressed on the star/delta starter, the motor is first connected in star producing 1/3 full voltage torque at one third full voltage current. The motor accelerates to full speed and then the starter, after timing out, changes to delta by first opening the star contact or, and then closing the delta contact or. When the star contact or is open, current is no longer able to flow through the windings because one end is open circuit.This causes transient torque and currents that are much worse than the full voltage conditions. The open transition stage can be eliminated by fitting an interlock [17].In the starter available all this is done automatically by the automatic star/delta starter.

5.1.3 Wiring of the star/delta starter

[18]



kW	FLA	SET O/L
5,5	12	6,92
7,5	16	9,24
11	23	13,28
15	30	17,32
18,5	37	21,36
22	43	24,83
30	59	34,06

kW	FLA	SET O/L
37	72	41,57
45	85	49,07
55	105	60,62
75	140	80,83
90	170	98,15
110	210	121,24
132	250	144,34

Figure 21: Wiring of the starter

After looking at the rating of the starter, the automatic starter is rated to a maximum input power of 7500 W (highlighted in figure 21). Anything above this the starter will trip. This value is low, during the load tests the generator was safely loaded to a load of 7210 W which had a corresponding input power of 9100 W which is above the rated value of 7500 W of the starter. It would be best to change the rating to a maximum input power of 11 kW instead of 7.5 kW so that the generator can take more load.

5.2 Cooling mechanism

Section 2.3.2 which describes the characteristics of the 400Hz generator and the tests on the cooling problem described in section 3.2.5 confirm that the cooling of the generator is a big issue. Section 2.3.2, shows that the 400Hz generator needs to be force cooled. It describes that the generator needs to be force ventilated at 30 mbar, the alternator force cooled at a flow rate of 100 g/secs and the braking system cooled at 130 g/secs.

In order to come up with a cooling mechanism, two important factors need to be known:

i the airflow direction through the generator

ii the airflow rate to achieve the necessary cooling

5.2.1 Airflow direction

Referring to figure 22below, the airflow direction of the 400Hz generator can be illustrated. The generator has three distinct sections labelled 1, 2 and 3. Section 1 houses the alternator , section 2 the electro-mechanical speed drive and section 3 houses the eddy current braking system. The airflow inlet as shown below, is through the ventilation openings across sections 1 and 3. The airflow outlet is through the middle section, section 2.

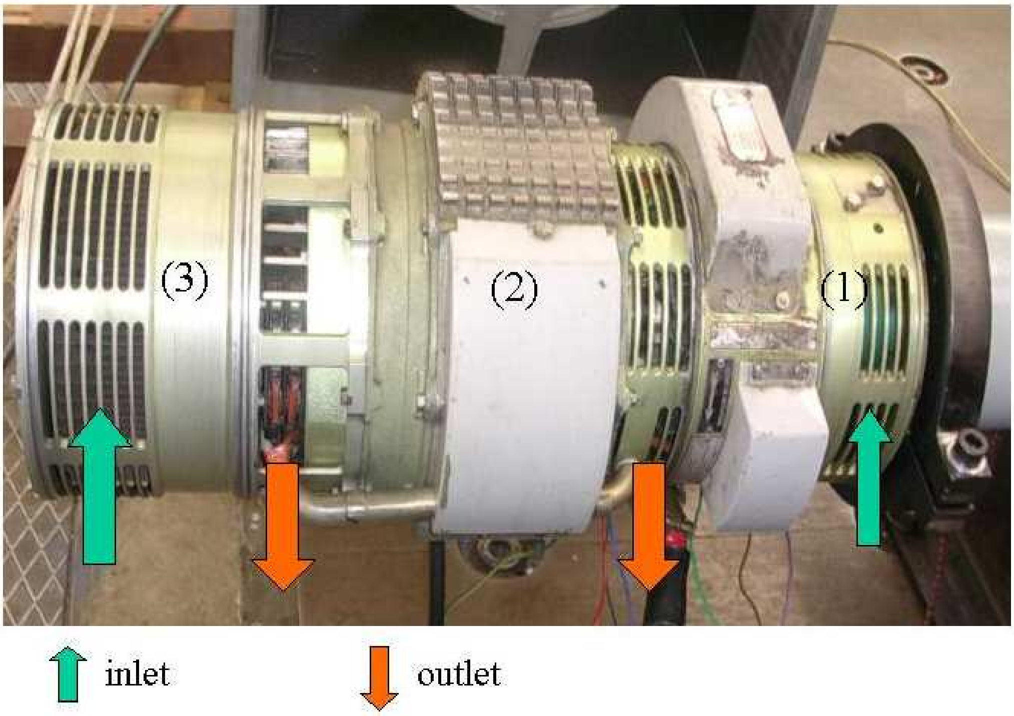


Figure 22: Airflow direction

5.2.2 Airflow rate

Under the characteristics of the 400Hz generator (refer to section 2.3.2), it is shown that section 1 (the alternator) needs to be force cooled with a flow rate of 100 g/secs while section 3 (the eddy current braking system) needs to be cooled at 130 g/secs.During the implementation phase, a centrifugal fan with an air filter will be used as the source of the cooling air. The important parameter in choosing the right fan will be its flow rate, that is the centrifugal fan used, must be able to provide the relevant flow rates to keep the 400Hz generator cool.Most duct fans on the market have their flow rate quoted in cubic feet per minute (cfm). Therefore the flow rates of the alternator and brake need to be converted to their respective values in cubic feet per minute.

This is done in the following way:

- the specific density of air, ρ = 0.0013 g/m^3
- 1 m^3= 35.314667 feet^3
- to change to from g/secs to m^3/minute ,this formula was used $cfm = \frac{g}{secs} \times \rho \times 60 \times 35.314667$
- the values obtained were 100 g/secs = 275 cfm and 130 g/secs =358 cfm

Therefore a duct fan with a flow rate greater than than 358 cfm will do. Preferably one with a value between 380 and 400 cfm supplying sections 1 and 3.

5.2.3 Proposed cooling mechanism

The centrifugal fan will blow the air through the cooling coupling mechanisms labelled 1 and 3(represented by the green boxes) which fit on the ventilation openings on sections 1 and 3. One duct fan will probably supply both sections through flexible ducts like those used in swimming pools. The cooling coupling mechanism labelled 1 is available but a similar coupling mechanism needs to be constructed that fits across the openings across section 3. The red box represents the casing that will be placed over the mid-section and has a 10 cm opening on the side as the outlet of the air blown in. The outlet is connected to an extraction fan via a flexible duct.

note: all dimensions are in cm

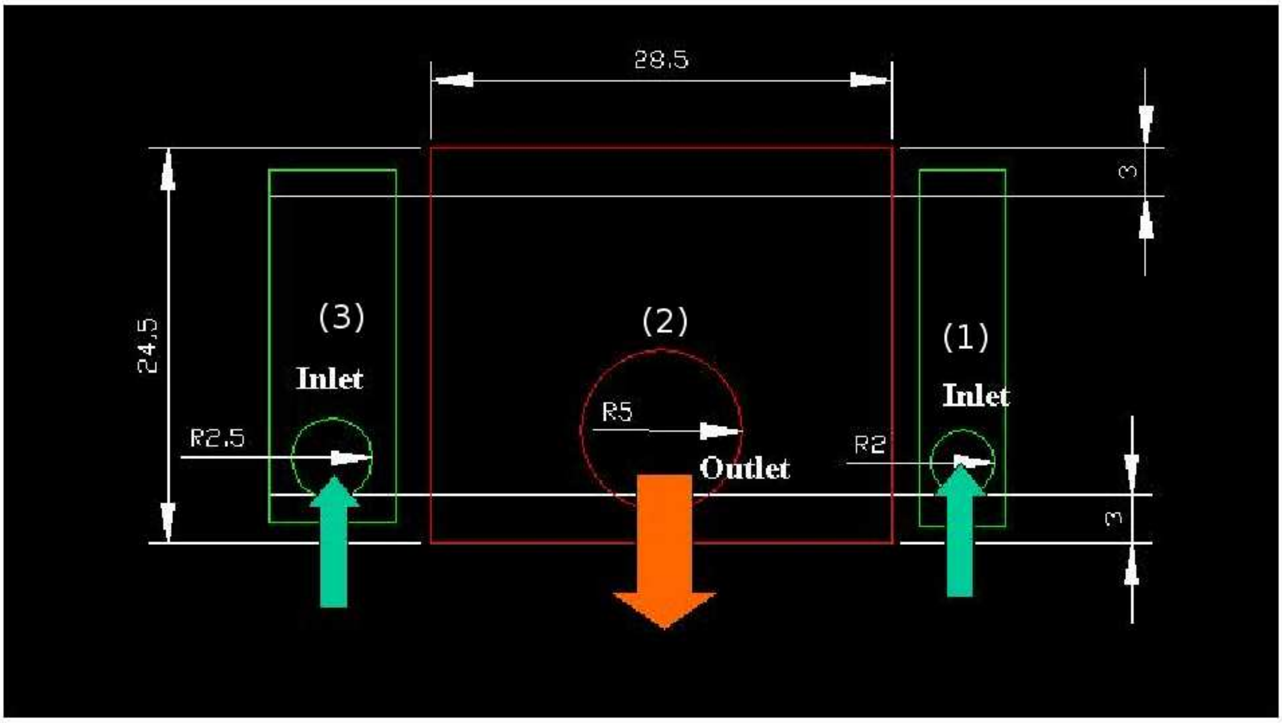


Figure 23: Side view of cooling mechanism

Figure 24 below provides a better description of the construction of the casing around the mid-section (red box). Originally perspex was the material that the casing was supposed to be made out of. But after consultation from Chris it would be better to use a thin metal which is easier to work with because it can be easily moulded. The casing is a 24.5 ×24.5 box which is cut on the sides so that the generator fits right in the middle of the box as shown below. The box is cut perpendicularly through the centre so that it can be opened up and fitted around the generator using a clipper and hinge system.

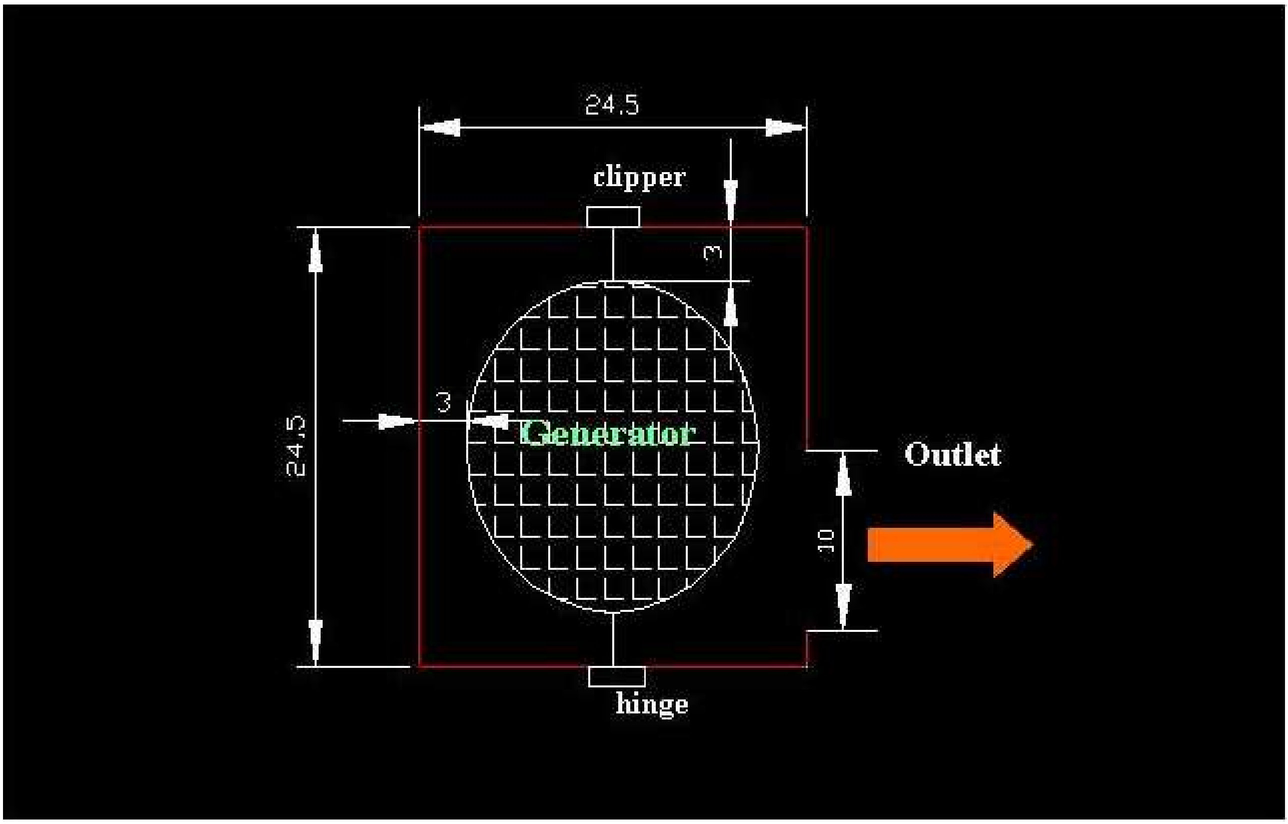


Figure 24: Front view of cooling mechanism

5.3 Platform design

Currently there is no platform were the 400Hz generating system will seat. Since the 400Hz generator is heavier than the induction motor, the generating set arrangement has a tendency of tipping towards the generator. A platform needed to be designed that stabilises the whole system. The main requirements of the platform was that of preventing the system from tipping over but and also, that the supports under the platform all needed to be under compression hence the centre of gravity point of the generating set had to be found.

5.3.1 Tipping point

As illustrated in figure 25 below the edge of the platform is the tipping point of the whole structure. Therefore the longer you make the platform, that is the more you move the tipping point to the left, the more stable the system becomes from tipping.

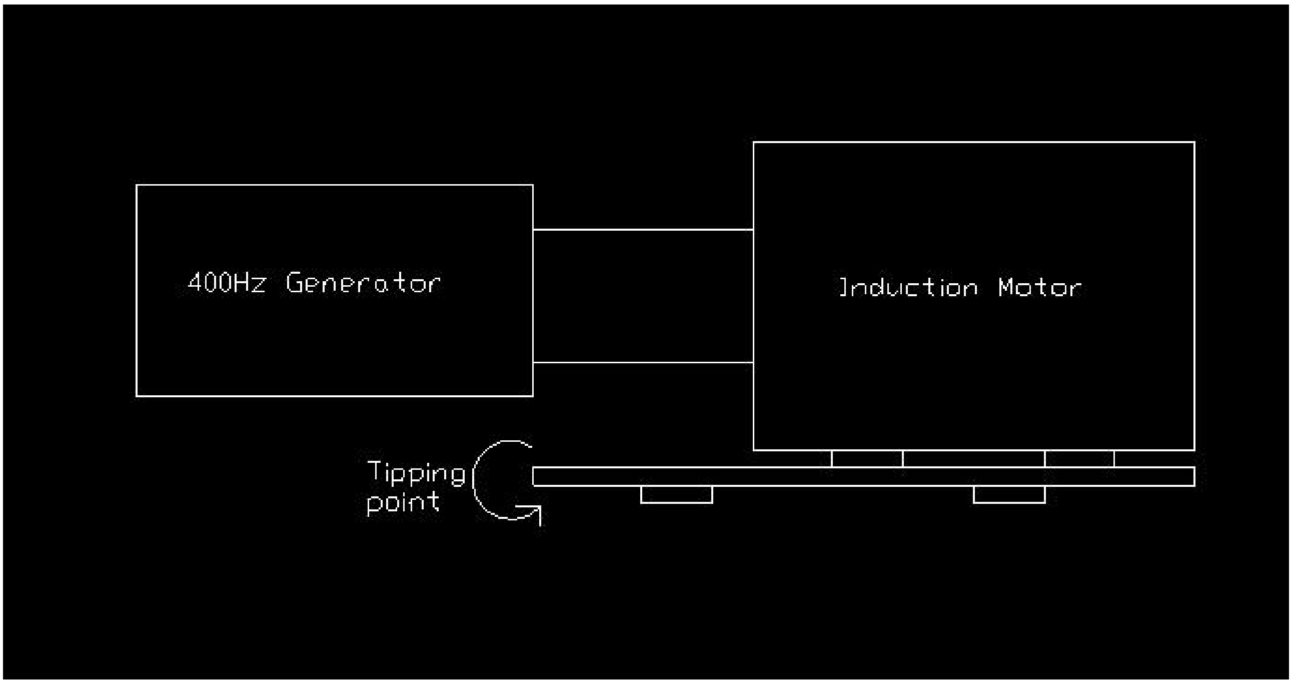


Figure 25: Illustration of tipping point

Therefore the platform was designed to be slightly longer than the generating set so as to completely rule out the possibility of the whole structure tipping over.

5.3.2 Supports under compression

The other requirement that the supports of the platform be under compression depended on knowing the position of the centre of gravity. This position was important in that this would enable us to put the supports equidistant from this point and hence put the supports in positions were they would under compression as illustrated in figure 26 below.

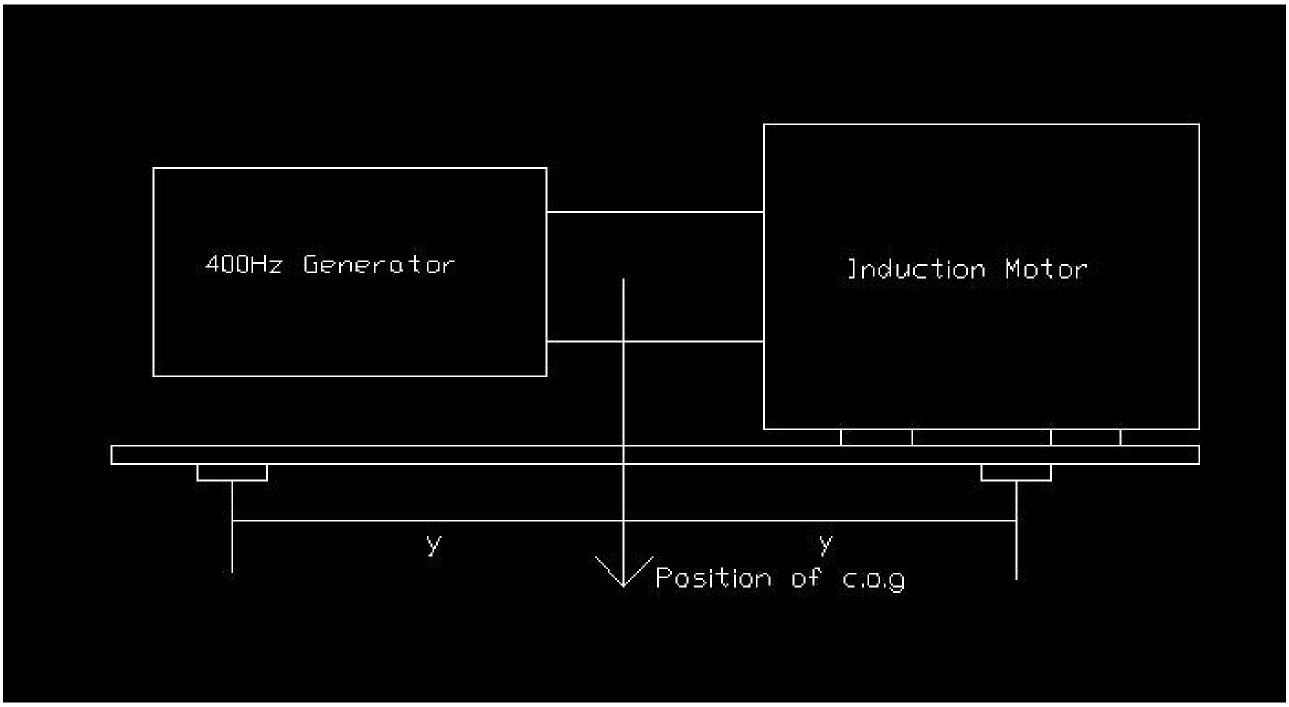


Figure 26: Positioning of supports

The position of the centre of gravity was found to be approximately 0.59m from the left edge of the platform. Hence the supports were placed 0.45m from the centre of gravity. This is represented as length y in fig. 26. The method used for finding the centre of gravity involved using one of the big cranes in the machines lab, putting a supporting rope around the motor-generator system which was connected to the cranes hook and then lifting the system slightly until it just begins to tip. The position of the supporting rope was changed until the position where the system was balanced by the rope was found. This position was the centre of gravity point.

5.3.3 Proposed Platform Design

After the design requirements were taken into consideration, the following platform design diagrams were arrived at. The platform material suggested is steel of a thickness of 3 cm with the following dimensions:

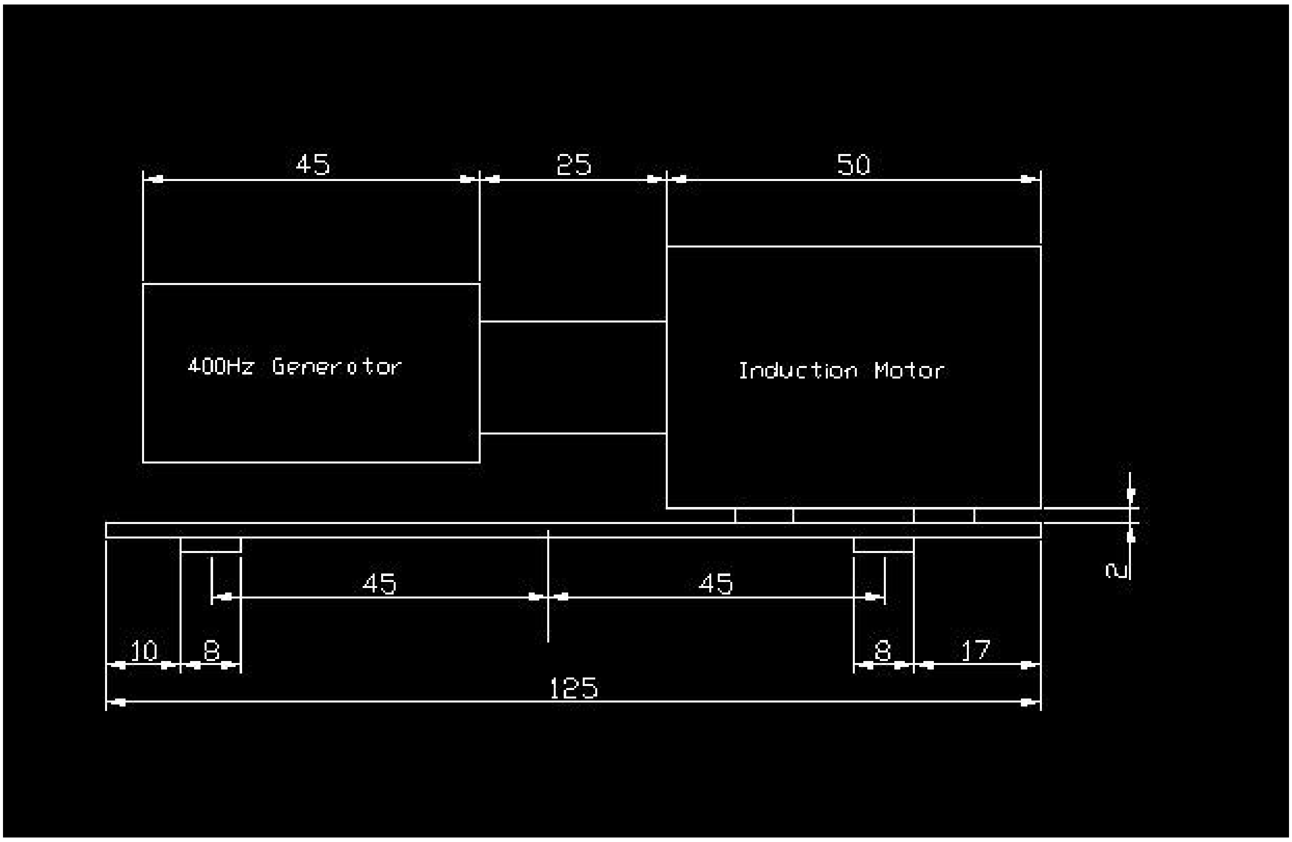


Figure 27: Side view of generating set on platform

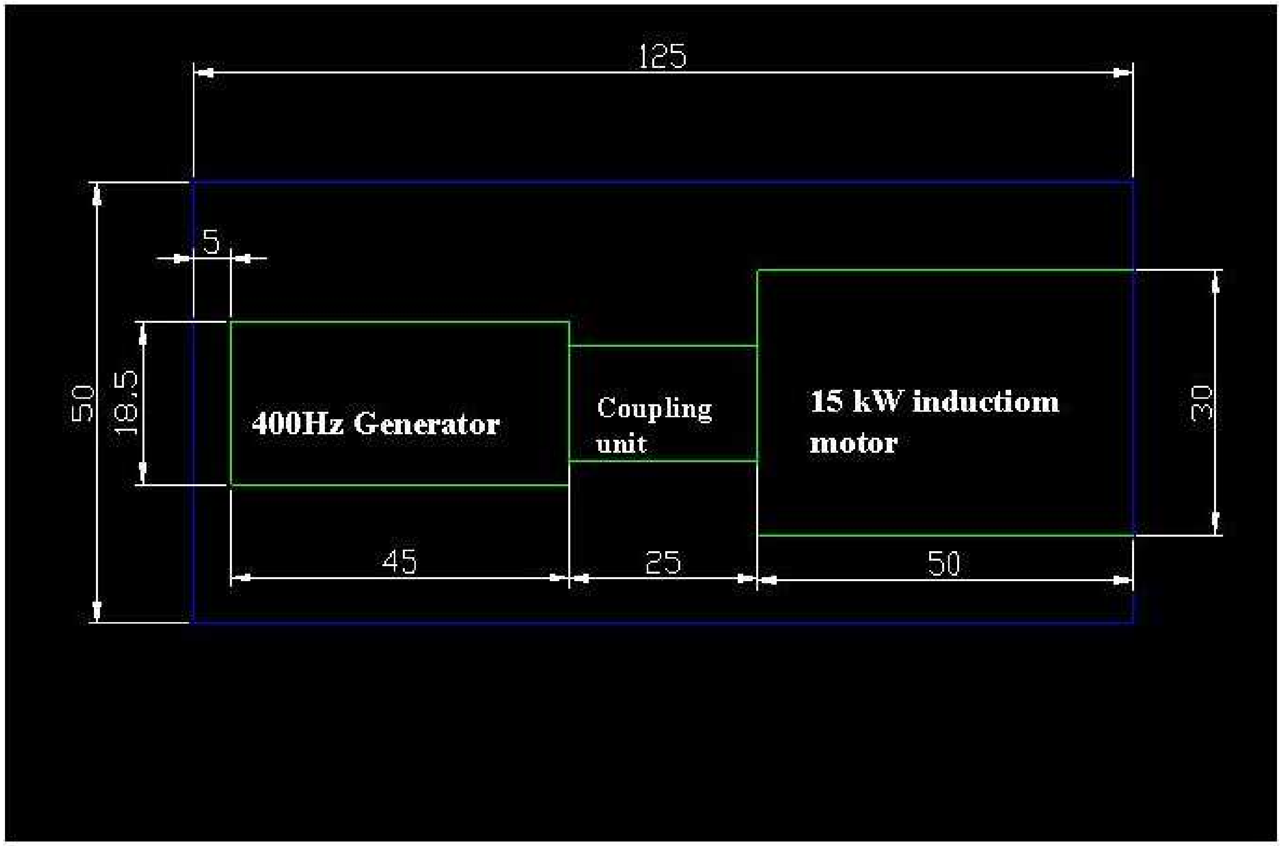


Figure 28: Top view of generating set on platform

6 Conclusions and Future works

Based on the information in the previous chapters, the following conclusions and future works have been drawn.

6.1 Conclusions

6.1.1 The 400Hz power supply works efficiently up to 7400 W

The 400Hz power supply will safely and efficiently produce 3 phase, 400Hz power for the radar laboratories up to a load of 7400 W. It's worst efficiency is about 80 % because when the 400Hz supply was overloaded with 9723 W (bear in mind that at 2940 rpm, the rated power is 12 k VA), it's efficiency value was 76 %. It's best efficiency value during the tests was 87 % at a load of 4740 W. The 400Hz power supply would be safe to load until a load of 7400 W.

6.1.2 Rating on the starter mechanism must be changed

The star/delta starter has been rated to a maximum input power of 7500 W. But the 400Hz power supply can safely take a load of 7400 W which requires an input power of 9100 W. By maintaining the rating of the starter at 7500 W input power, you are restricting the loading range of the 400Hz power supply to loads that wont require an input power of greater than 7500 W. The rating must be taken up to a maximum input power of 11 kW so that the load range can be increased.

6.1.3 Wiring must be completely redone

One of the first unexpected problems faced was faulty wiring. Before the 400Hz power supply system is commissioned, the wiring of the whole system must be redone to the correct standards (refer to section 6.2.5).

6.1.4 Frequency resistors limit loading of the system

Though the addition of the frequency limiting resistors solved the big problem of the system ”hunting”; it brought about limitations in loading in that what ever load is added to the 400Hz power supply essentially adds to the 3 kW load already present on the generator due to the frequency limiting resistors.

6.2 Future works

All the future works described in this section must be done before the 400Hz power supply is commissioned.

6.2.1 The starter mechanism must be tested

During the testing of the 400Hz power supply, a variable speed drive (VSD) was used as the starting mechanism to steadily rise the speed of the induction motor from 0 to it's rated speed of 2940 rpm. But the combination of the VSD and the generator's electro-mechanical speed control drive lead to the big problem of ”hunting”. This was solved by adding frequency limiting resistors but this brought up a limitation in that the 400Hz power supply had a permanent 3 kW load on it.

The setup on level six will utilise a star/delta starter as the starting mechanism. An automatic star/delta starter is currently implemented on level six which needs to be taken down to the machines lab for testing with the supply system. The electrician who installed it must be contacted so that he can remove the starter because it is connected to the supply lines on level six. The frequency limiting resistors should be disconnected from the setup (by removing connector J4d)[refer to figure ..] when the star/delta mechanism is connected to the 400Hz power supply and the system should be run. This exercise should be done to verify that the use of the VSD caused the ”hunting” problem. If the frequency limiting resistors can be removed, a greater load range can be utilised by the 400Hz supply system. Instead of 3000 W to 7400W but from 0 W to 7400 W.

The rating on the star/delta starter must be changed so that the generator can be loaded with bigger loads that require an input power of more than 7.5 kW. The electrician who installed the device should be contacted to change the rating to a maximum input power of 11 kW.

6.2.2 Cooling mechanism must be implemented

The cooling of the generator is vitally important. During testing the running time of the generator was restricted to 20 minutes to prevent overheating. A cooling mechanism such as the one described in section 5.2 must be implemented. A duct fan with an air filter will blow air into the inlets of the generator and extraction fan will be connected to the outlet. Suitable fans need to be identified. The middle section casing should be made out of a light metal instead of perspex.

A temperature interlock needs to be implemented which is a device that monitors the temperature of the generator and turns off the system when the temperature exceeds a set value. The set value must be like 65^0C so that the generator switches off before it reaches it's maximum value of 80^0C. An adjustable thermocouple is recommended as the temperature sensor and can be placed on the heat sink on the generator.

A pressure transducer must also be implemented that senses the pressure and is connected to a circuit that does not start the supply system until the right amount of pressure (3000 Pa) is on the brake and alternator openings. The supply system must not run if it isn't being effectively cooled.

6.2.3 Platform must be constructed

The platform design described in section 5.3 must be constructed. The method used to find the centre of gravity involved finding the position where the system was balanced when lifted slightly by a crane. This value must be validated by using moment of inertia calculations before the design is implemented.

6.2.4 All external circuits must be placed in one box

Currently, the 28 V signal supply unit and the adjusting unit are housed in separate boxes. To make the wiring arrangement more efficient instead of the current arrangement where wires go in all directions, all external circuits should be housed in one unit. The box should also include these circuits:

. a temperature interlock circuit which turns on an LED and switches off the 400Hz supply system when the generator's temperature exceeds a set value (e.g 65^0C)

. a pressure sensing circuit so that if the pressure on the brake and alternator openings is less than 3000 Pa, the supply system should not start.

. an LED indicating whether the regulator is on and any other relevant circuits not mentioned

6.2.5 Wiring must be completely redone

The wiring harness that is currently available had proved to be unreliable. Before the 400Hz power supply is commissioned the wiring harness of the system needs to be completely redone to the correct standards. The correct method involves:

. removing every crimp contact from the connectors (a special tool is required to remove the contacts which is currently not available at UCT)

. removing the wires from each crimp contact by holding the wire and the twisting the rear of the contact until the contact slides off

. cleaning the contacts and connectors with a contact cleaner (available from Chris)

. soldering the wire into the crimp contact (no solder should stick out of the rear of the contact)

. placing the crimp contacts back into the connector as described in section 3.2.3

References

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