Design and Development of a Variable Frequency Drive Test Bench Prototype and Testing Regime for Repaired Drives

by

Akshat Kukreti

Bachelor of Technology, Electrical and Electronics Engineering
SRM Institute of Science and Technology,
Chennai, India, 2019

A Project Submitted in Partial Fulfillment of the Requirements for
the Degree of

MASTER OF ENGINEERING

in the Department of Electrical and Computer Engineering

Design and Development of a Variable Frequency Drive Test Bench Prototype and Testing Regime for Repaired Drives

by

Akshat Kukreti

Bachelor of Technology, Electrical and Electronics Engineering
SRM Institute of Science and Technology,
Chennai, India, 2019

Supervisory Committee

Dr. T. Ilamparithi, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Navneet Popli, Departmental Member
(Department of Electrical and Computer Engineering)

Abstract

Small and medium-sized industrial control panel makers, systems integrators, and repair shops frequently encounter issues with Variable Frequency Drive (VFD) testing. These companies frequently rely on third parties to evaluate their VFDs prior to field commissioning, increasing expenses. To address this issue, an in-house test bench was created for a control systems integrator's maintenance department (KJ Controls).

The test technique includes static, functional, and operational testing of the drive under test. To completely verify the VFD's operational capability, it must be connected to a loaded motor. A load motor/dynamometer is required for this test. For this, a prototype was created in the repair department using readily available and stock components. This configuration facilitated the testing of the operation and functioning of a 2 HP drive.

The tests run on the drive included a static test, a free run test, a motor stall test, and a speed regulation test. These were then suitably recorded on a factory acceptance test sheet. It was eventually calculated that having an in-house testing system would save the company at least 10% on the total cost of testing repaired VFDs. It was predicted that the payback period for such a test bench arrangement would be close to three years.

Table of Contents

List of Figures

List of Tables

Glossary

DUT- Drive Under Test

Dyno- Dynamometer

HP- Horse Power

MMF- Magnetomotive Force

MUT- Motor Under Test

PLC-Programmable Logic Controller

PWM- Pulse Wave Modulation

RMS- Root Mean Square

RPM- Revolutions per minute

THD- Total Harmonic Distortion

VFD-Variable Frequency Drive

Acknowledgments

First and foremost, I would like to thank my Supervisor at UVic, Dr Ilamparithi for his unwavering belief and support throughout this project and the MEng Program.

I would also like to thank everyone at KJ Controls for supporting me and helping me whenever I needed them. I would like to extend my gratitude to the CTO, Mr. James Boileau, and the repair technician, Mr. Jesse M, who went out of their way to help me.

I would also like to thank my friends and family for always motivating me and being there when I needed them.

Finally, I would like to thank God, the Almighty for always being by my side and making this project a possibility.

Dedication

To all my friends and family in Canada and back home.

Thank you all for everything!

CHAPTER 1- INTRODUCTION AND OBJECTIVES

1.1 Variable Frequency Drives and their Testing

Industries using large motors for a part of their operations are faced with an inherent need to reduce the large inrush current on their motor. Based on the intent of the application, a reduced voltage starter (also known as a soft starter) or a VFD might be used. If the purpose is solely starting the motor, then a soft starter is the right choice [1]. However, if the application requires speed control, a VFD has to be used. By gradually ramping up the voltage, a VFD inherently controls inrush current. Therefore, a VFD provides the benefit of a wide range of speed control as well as a reduction in start-up current. It is also worth mentioning that by implementing speed control, most industries can run their operations much more efficiently [2].

Variable Frequency Drives(VFDs) require a series of maintenance tasks to be performed periodically to ensure drive longevity and accuracy. In the industry, most VFDs face harsh environments and severe operation cycles. This leads them to malfunction at some point in their lifetime even though they are rated for those environments [3].

On examining the stages of a VFD for better understanding, one may assess the components that make up a VFD. This can also provide a broader idea of the maintenance and understanding of the failure points/components [5].

Figure 1.1 below shows the stages of a VFD. The four main parts that comprise a VFD are the rectifier, the DC bus section, the inverter section, and the control unit. Thereafter, Table 1 describes each stage in detail with the possible point of failure(s).

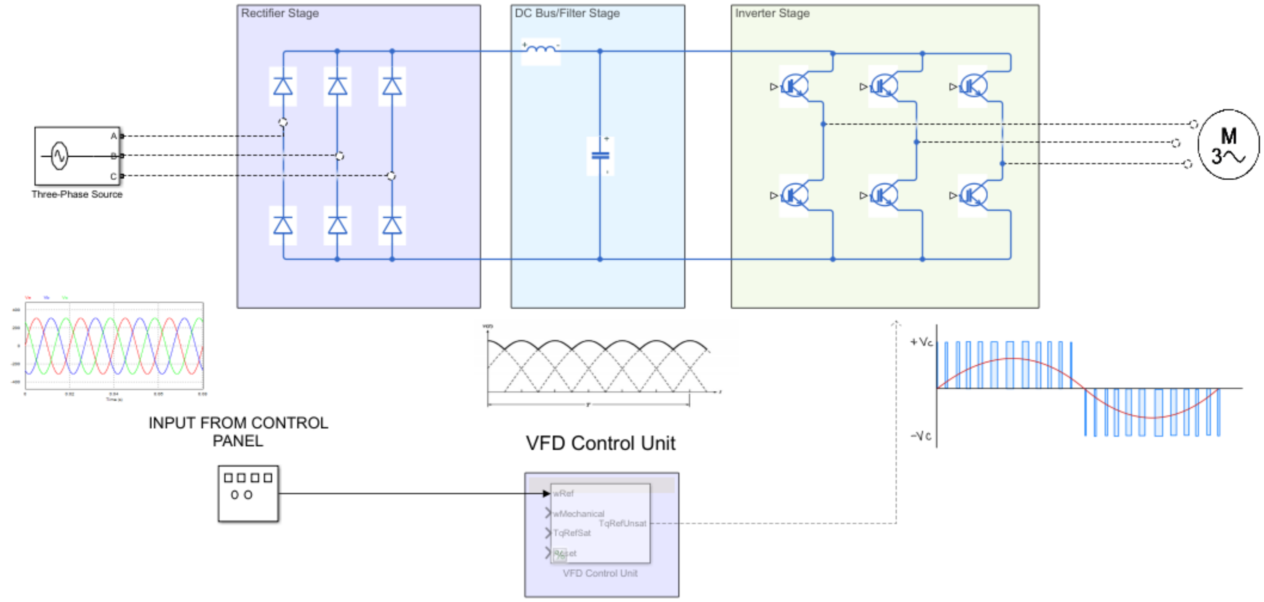


Figure 1.1 Various Stages inside a VFD [6].

Table 1.1 Different stages of a Variable Frequency Drive and common points of failure.

VFD Stage	**Description**	**Points of Failure**
Rectifier Stage	The rectifier converts 3-phase or single-phase AC to DC Voltage. This stage contains diodes in a bridge configuration.	Diode modules often fail due to peak transient voltage from the input. Also, in cases where the DC bus capacitor is not fully discharged, large magnitude current can flow through the diode rectifier circuit damaging them. To rectify these issues, a line reactor will help in protection of diodes.

DC Bus/Filter Stage	This acts as a storage point for the rectified DC. LC filters are placed before the inverter stage to remove any residual AC components.	Filter capacitors are a major failure point, often due to improper equipment care. They also reach their end of life faster due to continuous exposure to heat. As a part of preventative maintenance, cooling fans and ducts should be kept dust free and adequate temperatures must be kept in the VFD’s surroundings.
Inverter Stage	This stage converts the DC into pulsed sine wave i.e. near-sine-pulse wave using PWM. The AC signal produced would not be pure sine wave but mimic AC. This is good enough for the motor to run. IGBTs with feedback diodes are used in the inverter stage.	IGBTs are extremely sensitive to heat and prone to fail.
Control Unit	This unit takes input from the user and sends gate pulses to the IGBT. There are other	The main failure point is the control circuit board i.e.

	special functions this unit does like control braking and stopping. It can have a separate control power or use the supplied power. In most applications, a VFD is required to communicate to an external controller like a PLC.	components on the printed circuit board.

Before commissioning these drives in an industrial or commercial setting (field commissioning), a VFD undergoes a series of tests. Some of these functional testing requirements as per most manufacturers [7] are:

- Three-phase input power measurement.
- DC Bus Voltage Measurement.
- VFD Output Power/Motor Input Power.
- Motor Mechanical Power.

In Figure 1.2, the markings 1,2,3, and M point to the components which are a part of the test process.

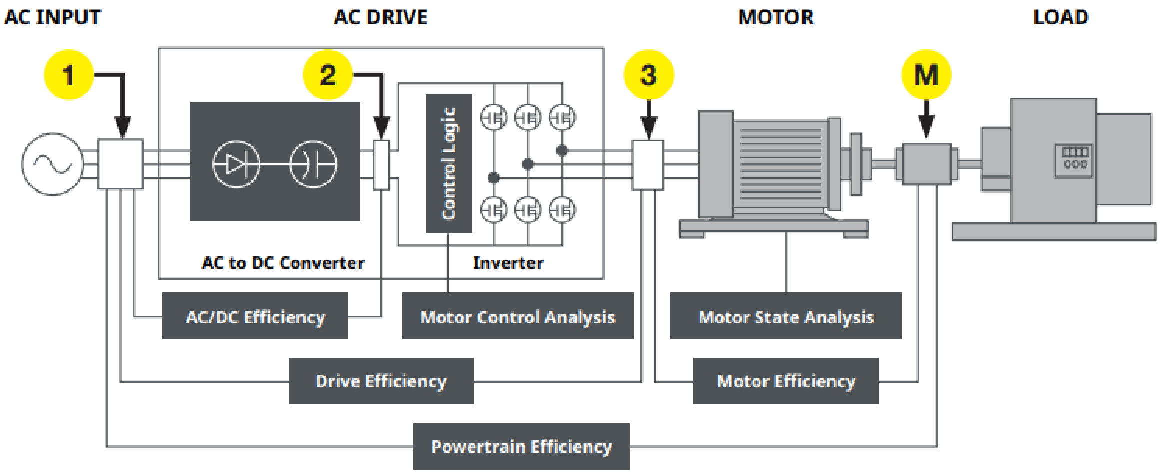


Figure 1.2 A 4-Step Testing Procedure for VFDs [7].

Explained below briefly, are each of the testing steps.

Number 1 shows the measurement of AC Input, this is important to measure because:

a) The input current drawn by the VFD has harmonics and is distorted because the rectifier containing diodes acts as a non-linear load. These distortions must be controlled using line reactors. Line reactors are linear loads that increase the overall linearity of the load on the system. This will bring down the total harmonic distortion of the system (discussed below).

b) These harmonics cause the line voltage to sag during the high load periods of a motor. It is therefore essential to monitor the effect of these harmonics and measure the input regularly [7].

According to IEEE 519-2022 standard, harmonic voltage distortion on power systems with 1kV or less is limited to 8% total harmonic distortion. Similarly, 69 kV or less is limited to 5.0% total harmonic distortion (THD), with each harmonic limited to 3% [8]. THD is expressed as the harmonic content's root-mean-square divided by the fundamental quantity's root-mean-square, represented as a percentage. In a practical industrial scenario, industries running VFDs aim to keep their total harmonic distortion limited to 5-8% [9]. This is practically achieved using line and load reactors which act as harmonic filters.

Number 2 shows the measurement of the DC bus voltage. The DC bus acts as an ‘intermediate buffer’ between the fixed input voltage at a fixed frequency and the variable voltage, variable frequency output to the motor.

It is essential to measure DC bus voltage for the following reasons:

- Conditions like braking and overhauling loads causes the motor being driven to act like a generator. This causes energy flow back to the VFD. Here, the diodes prevent current flow to the line side of the VFD and this in turn causes the DC bus capacitors to overcharge. This phenomenon causes an overvoltage at the DC bus. The condition must be detected quickly and the drive must be protected against it.

- DC bus voltage is also a measure of the input voltage magnitude and the rectification efficiency. Therefore, it is an important guide while troubleshooting the rectifier stage. In addition to this, output voltage can be compensated for by changing the inverter modulation index which depends on DC bus voltage (1.1). Most VFDs have a parameter to change the modulation index.

$$Modulation\ index/\ Voltage\ utilization\ ratio\ = \frac{Vout_{peak}}{(0.5 \times DC\ bus\ voltage)}$$

……………(1.1)

- A sudden voltage drop on the DC bus can also be indicative of a loss of phase or low input voltage.

(1.2) below is the expression for calculating the DC bus voltage for a VFD. Here V_{in} is the input line voltage supplied to the VFD.

$$DC\ bus\ voltage(under\ no\ load)\ =\ Vin_{rms} * \sqrt{2}$$

…………….(1. 2)

For a 480VAC Input, the DC Bus should be $480 \times 1.414 = 678\ VDC$. It must also be noted that this value can dip slightly when the motor is loaded due to increased current draw by the motor.

(1.2) can be modified for a loaded condition if the voltage output equation of a 6-pulse rectifier is considered. Here V_{rms} is the RMS line input voltage, and V_m is the peak input voltage.

$$Vdc = \frac{3}{\pi} \times Vm = \frac{3}{\pi} \times \sqrt{2} \times Vrms\ \cong 1.35 \times Vrms$$

…………….(1.3)

From above, the DC bus voltage should be close to 1.35*460= 621 V when the VFD is driving a loaded motor.

Most manufacturers provide a range of acceptable DC bus voltage. If out of range, the drive sends a fault signal and trips.

As an example, for a 380-480VAC drive, the undervoltage limit is 390VDC and the overvoltage limit is 810VDC [10].

Number 3 points to the output of the VFD. This needs to be measured and its power quality must be observed. The high-frequency signals used to switch the IGBTs create a distorted waveform going to the motor. These sudden changes create motor heating issues and shorten motor life. It is recommended to have a load reactor or a dv/dt filter (especially in case of a longer cable run) at the load side of a VFD. dV/dt filters help reduce the rate of change of voltage and reduce the traveling voltage spikes from reflecting and amplifying [8].

Finally, M points to the measurement of mechanical power developed by the motor. For this measurement step, a dynamometer is required which calculates the motor's torque and speed. These values are then used to calculate the mechanical output power as given in (1.4). This step ensures the proper working of a VFD drive and its ability to control speed and ensure the motor produces the expected torque.

A dynamometer is useful in calculating the motor's mechanical power and torque developed. It can help emulate a load on the driven motor. This eliminates the need for an actual load to be applied against the shaft.

To compute efficiencies, at least one of the three listed efficiencies: drive, motor, or powertrain efficiency must be identified. A dynamometer allows us to verify the powertrain or motor efficiency easily. This can be accomplished by estimating the motor's mechanical output power and determining the ratio of mechanical power output (P_{out}) and power input (P_{in}). Efficiency calculations have not been included in this work.

1.2 Overview of VFD Test Procedures

To create a VFD Testing procedure for the repair department, the existing VFD testing guide from KJ Controls was revisited [11]. Apart from that, online sources and white papers published by manufacturers were also considered. Chapter 2 discusses some of the sources for developing a VFD test procedure.

The tests for VFDs fall under three major categories:

a) Static tests: These tests are performed before the drive is powered up and ensure the integrity of the components used. This prevents any further damage to the device as defects are identified before powering up.

b) Functionality tests: These tests verify the basic functions of the drive. Functionality tests tell us how a VFD reacts to different conditions like faults, acceleration/deacceleration and speed control. By performing these tests, the VFD's control and protection features can be verified.

c) Performance tests: These tests are intended to validate the working of the VFD under loaded conditions. By applying varying levels or load or 'stress' the drive components behave differently simulating real world conditions. These tests can access the drive's behaviour to different loads and also provide us figures of merit. Some figures of merit that can be obtained from performance tests would be:

    i. Efficiency of VFD
    ii. Speed Regulation
    iii. Rise in temperature
    iv. Speed-Torque performance

The proposed tests for VFDs post-maintenance are as follows:

1. Static testing- These tests are carried out while the VFD is non-functional and turned off. Static testing consists of testing diodes on the rectifier side of the drive, components on the

control circuit board, and capacitances and IGBTs on the inverter side. This indicates if all of the VFD's components are intact and safe to operate.

2. Free run (No load test)- The motor is run at no load up to the rated speed and a plot between the expected output(theoretical) and the actual speed is obtained from the Arduino RPM meter. This plot tells us if the VFD can control speed as expected with good enough accuracy. This test will also ensure the functionality of the control circuitry of the VFD. At this stage, any external brakes connected to the drive may also be tested out. Also, DC bus voltage measurements can be taken to ensure the DC bus capacitors are in good shape. This test can be categorized as a functional test.

3. On load test with speed regulation- In this test, the motor is loaded using a dynamometer, and the torque and speed are measured. Loading occurs gradually by increasing the DC current applied to the stator of the load motor. This test validates that the VFD operates properly when controlling a loaded motor. The current demanded by the motor increases as the torque increases. The VFD then produces the required current, and this test confirms that it can do so. The second component of the test involves varying the applied load at a specific frequency. The VFD must ensure that the speed remains relatively constant after a few seconds. Manufacturers set a benchmark grade of 2–4% for speed regulation. This test can be categorized as a performance test as it is carried out by simulating real-world loading conditions.

4. Functionality test- A few functionality tests might be run based on the type of VFD being tested and the kind of parameters that can be set for it.

   a) Stress test for overload trip- All VFDs have a current limiting feature on overload. They allow a certain amount of current to flow for up to 10-60 sec before tripping with an overload fault. This is tested by applying excessive load on the motor until it stalls and then the VFD trips a few seconds later due to overload.

b) Trip on over/under voltage of DC bus- This is usually a configurable parameter within the VFD that senses the under or over voltage of the DC Bus. This usually presents a fault code and the drive stops. For testing this functionality, the ‘fault on under voltage’ parameter is set and the drive is turned off. During the turn-off process, the VFD will fault for a fraction of a second stating undervoltage at DC Bus. Fault Logs/History can then be read to confirm if the drive presented this fault.

1.3 Role of Dynamometer in VFD Test Bench

Dynamometers or ‘Dynos’- is an equipment that can measure the power output of a prime mover. The system under test in most cases is an internal combustion engine, a hydraulic or electric propulsion system, or a motor shaft.

In theory, a dynamometer monitors a system's torque (mechanical torque at the motor shaft) and speed (revolutions per minute of the output shaft) at any given instant. It also applies an opposition to the motor under test.

Accordingly, from the dynamometer's output of torque and speed, power can be determined as follows:

$$\text{Power in Horsepower(HP)} = \text{Work done per unit of time} = \frac{RPM \ \times Torque(lb - ft)}{5252}$$

……..........(1.4)

Here, 1 HP is equal to 746W or 0.746kW.

This forms the basis of the power computation from the outputs of a dynamometer. In the case of a VFD testing scenario, a dynamometer is a must. Measuring motor mechanical output power can be done only when the motor is in a loaded condition. A dynamometer will also be essential in calculating the motor and or drive’s efficiency.

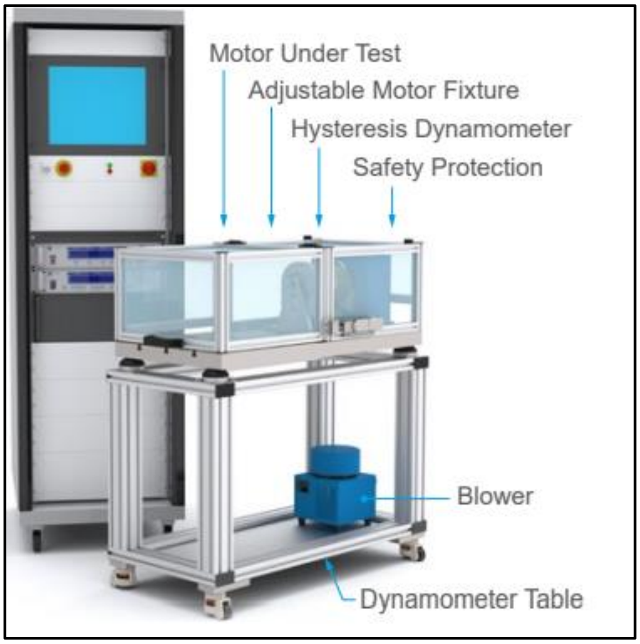


Figure 1.3 A custom-built hysteresis dynamometer system for motor testing by Magtrol Inc. [12].

The figure above shows an industrial-grade dynamometer test setup for motor testing. The company Magtrol deals with designing such custom units for facilities that require loaded motor testing [12].

1.4 Project requirement received from KJ Controls

KJ Controls and Contracting in Nanaimo is a small to medium-sized control panel shop that specializes in the assembly and manufacture of Motor Control Centres (MCCs) and Control Panels. As a CSA Certified control systems integrator, they work on projects in both public and commercial sectors. They typically operate in wastewater, mining, and forestry [13].

The entire facility includes two "panel shops," a fabrication station, a paint booth, an engineering department, a sales department, and a repair department.

Variable Frequency Drives are among the most significant and widely used components in the control and automation industries. This panel shop utilizes a VFD for both the control panel and the MCC projects. The sales department also carries new, open-box, used, and reconditioned VFDs. The repair section also specializes in repairing VFDs of all sizes and applications.

On an average, KJ Controls repairs about 7-10 VFDs a month. Certain months are slow but often a lot of repairs need to be done in a short period of time. Only a few of them are however tested as per requirement, at a test facility where they are shipped to. For the sake of simplicity, it has been assumed that 5 VFDs would require testing each month.

KJ Controls' request was for the construction of a VFD Test Bench. This would feature a dynamometer for loading the induction motor driven by the VFD. Other requirements included the ability to test VFDs with a power rating of up to 2 HP (1.5 kW). After creating this prototype, a plan for testing repaired VFDs was to be formulated. Future scaling of this prototype was suggested to enable it to test larger VFDs and be suitable for use in the rugged shop environment. It was recommended that minimum purchasing was done for this prototype design.

1.5 Objectives of this project

The objectives of this project were set up keeping in mind the requirements set forth by KJ Controls. The main objectives of this project have been defined below.

1. Build a test bench prototype for performance and functional testing of a VFD. This prototype design would achieve the following:
    - Test a 2 HP Allen-Bradley PowerFlex 40 Series VFD (22B-E3P0N104) which is out of commissioning and the product has been discontinued.
    - Use this VFD test as a basis for future tests and scaling the design to test bigger VFDs.

- Produce a cost-effective design that leaves a bigger margin for future scope and expansion. Major components used for making the prototype would be repurposed from other applications around the shop.

2. Develop a test routine for a repaired/refurbished VFD that will determine if the drive is ready to be commissioned back in the field.

1.6 Organization of this report

The other parts of this report have been organized as follows:

Chapter Two: Literature Review- This chapter presents the literature available on VFD Testing and the sources where useful references have been mentioned. Also, the primary inspiration of the work has been described in the last sub-section.

Chapter Three: Component selection for the test bench- This chapter focuses on how the components were selected and the in-depth discussion of every component's working. This section also discusses the DC dynamic braking strategy used to create a load on the driven motor.

Chapter Four: VFD testing prototype outcomes- This chapter discusses the results obtained when static, functional, and performance tests are run on the test VFD.

Chapter Five: Conclusion and future work- This chapter concludes the report by talking about the areas of improvement and action plans going forward.

CHAPTER 2- BACKGROUND ON VFD TESTING AND DYNAMOMETERS

2.1 VFD Testing Methodologies

When it comes to testing VFDs, limited information is available on how to test them after repair. However, one can refer to the manufacturer's recommendation as well as factory testing procedures. It was also observed that most available literature on this subject was application-specific. This means that different drives have different functional tests. Some common tests that are recommended by manufacturers have been identified [22].

Yaskawa, a manufacturer of VFDs has a procedural guide that tells us how to test the input diodes, DC bus capacitor, and output transistor. This resource includes six steps with instructions on how to test the input diodes and output transistors of a VFD. The diode test readings depend on the forward voltage drop of the diode which is a characteristic of the diode dependent on its doping. The values obtained in steps 1,3 and 6 below should be equal or almost equal under normal conditions [22]
An illustrated guide shows where to place the test leads and lists the expected multimeter reading.

Table 2.1: Summarizes the steps to be taken for the static test.

Step	**(+) Positive Multimeter Lead**	**(-) Negative Multimeter Lead**	**Multimeter Reading (Diode Test Mode)**
1	(-)Terminal	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	0.299-0.675 VDC
2	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	(-)Terminal	OL

3	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	(+) Terminal	0.299-0.675 VDC
4	(+) Terminal	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	OL
5	Brake Terminal 1	Brake Terminal 2	OL
6	Brake Terminal 2	Brake Terminal 1	0.299-0.675 VDC

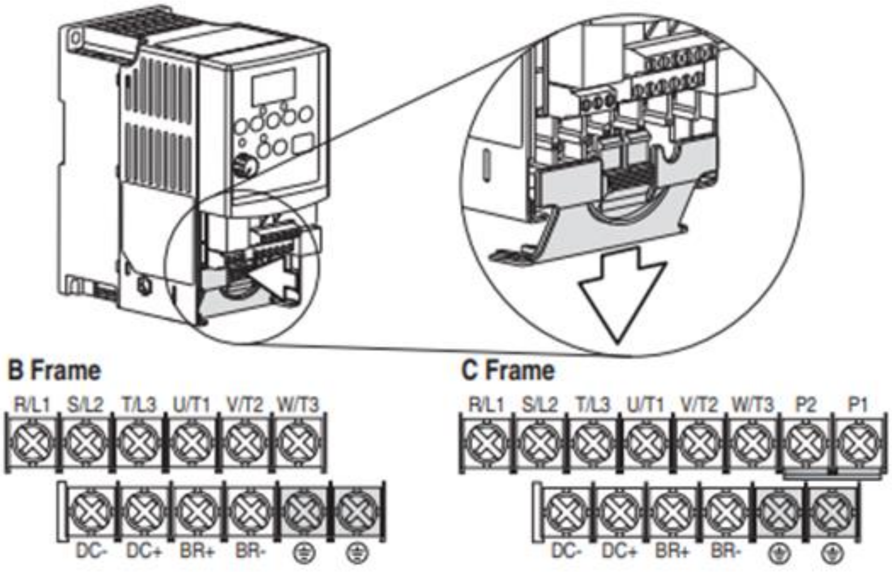


Figure 2.1: The typical VFD terminals referred in table 2.1 for a PowerFlex 40 VFD.

The next article that was referenced for the static test was one from Fluke [27]. It talks about the stages of the VFD and the internal components in the first part. This article then lists steps to measure the following:

a) DC Bus Voltage.

b) Voltage imbalance on the load side of the VFD.

c) Current Imbalance at the load side

d) V/F Ratio.

However, all these tests need a dedicated power analyzer or a Fluke VFD analyzer. Most of these values are displayed within the VFD itself. However, using an external scope to check them confirms the correctness of the internal VFD measurements. For instance, cross-checking the input current displayed by the VFD is required. This ensures that the CTs are intact and accurate.

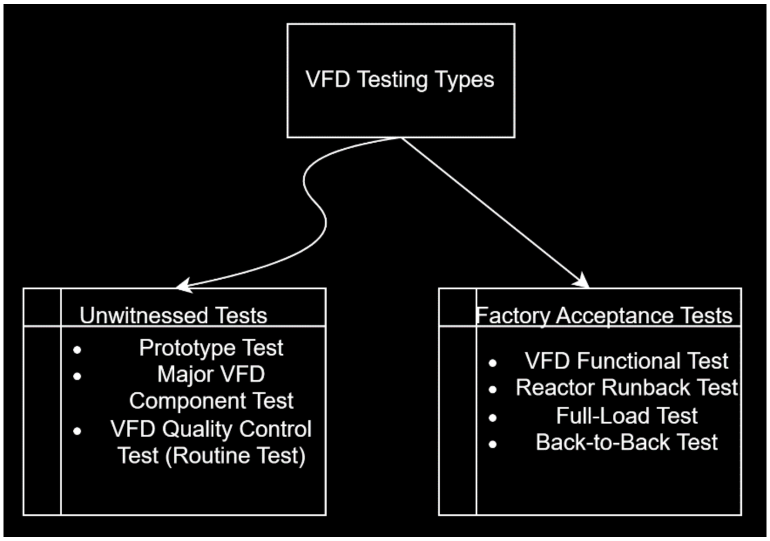


Figure 2.2 VFD Testing types and routine tests as listed by the manufacturer TMEIC Corp. [3].

A white paper by TMEIC Corporation talks about the acceptance testing of VFDs where VFD testing types have been explored and each one described briefly [3].

It further describes how routine quality tests are different from full-load tests. It also lists the industry standards on when a factory acceptance test is required vs an acceptance test. An acceptance test must be performed for a regulatory body like the CSA or UL. On the other hand, a factory acceptance test may be requested by the end-user or the customer at any point, especially after maintenance. Therefore, this sheds light on how KJ Controls will have to perform a FAT test when required by a client. At the end of this report, a custom FAT sheet has been created for a VFD FAT Testing scenario (Chapter 4.5).

Finally, as seen in the Fig. 2.3, the reference outlines two tests for full load testing. The back-to-back test would be ideal for an active front-end drive that uses IGBTs instead of diodes for AC to DC conversion.

The runback test shown in Fig 2.3 would be ideal for a regular passive front-end VFD, however, costs to secure the runback reactor and size will be an issue. Therefore, a dynamometer at the load end is a niftier solution and can be used for drives of all sizes and kinds.

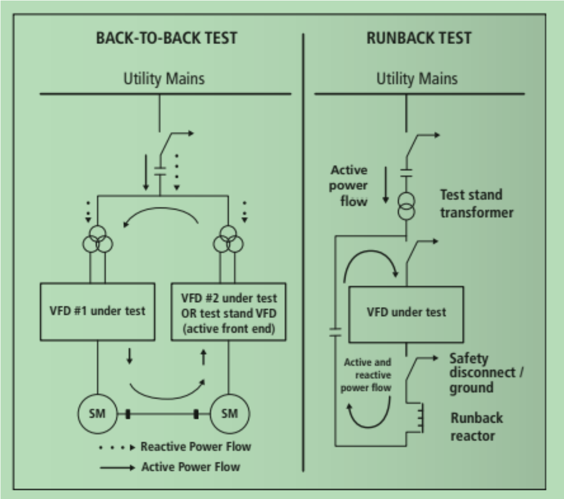


Figure 2.3: The two kinds of full load tests that can be performed on VFDs [3].

A typical testing facility to which KJ Controls outsources it’s VFD testing requirements [4] performs some or all of the tests listed below on the VFD. Tests are decided oIn a case-by-case basis according to repair done or problems reported as well as the VFD specifications.

a. Static tests for component level integrity.

b. Functionality tests by simulating fault conditions and parameter modifications.

c. Performance testing- On light load, full load, excess load, application specific loading.

d. Harmonics testing to identify the level of harmonics the VFD produces.

2.2 Types of Dynamometers

There are two primary subcategories of dynamometers- Power Absorption and Inertial Dynamometers. The inertial dynamometers use the known value of inertia of a mass being moved at a given speed and accelerating at a particular rate to calculate torque. Flywheel dynamometers are a type of inertial dynamometers.

For motor testing in particular, power absorption dynamometers are preferred whether it be a test bench/test bed or electric powertrain testing. [15]

Types of power absorption dynamometers include:

1. Hysteresis brake dynamometers- Provide accurate torque control over a broad speed range by using magnetic hysteresis. This dynamometer creates a regulated frictionless braking force on a ‘rotor drag cup’. The motion of the shaft is restricted by the magnetizing flux field applied to the pole structure that holds the rotor cup in place. The drawback of this dynamometer is that it can only test medium power range motors (up to 20 HP) and the setup is expensive [12].
2. Eddy current dynamometers- Produce a magnetic field that opposes the rotation of a rotating disc by creating eddy currents, which makes it perfect for applying loads smoothly and continuously in high-speed, high-power situations [12].
3. Powder type dynamometers- This dynamometer uses magnetic powder to obstruct motion. This is applicable for both low- and high-speed applications since the powder changes its properties(hardens/softens) in reaction to an electromagnetic field [12].
4. Prony brake dynamometers- They apply a controlled braking force to a rotating drum to measure torque. This method is frequently employed for straightforward, inexpensive applications where exact measurements are not as important [15].

5. Hydraulic brake dynamometers- This is appropriate for heavy-duty, high-power testing by creating resistance using fluids. It generates resistance via fluid dynamics, which uses the fluid's resistance to movement to create a load [15].

6. Motoring or absorbing dynamometer- In this dynamometer, precisely controlling the load conditions is possible. It does so by using two electric machines operating against each other, one functioning as a generator and the other as a motor. Moreover, this type of setup is more intuitive to implement. This type of dynamometer is employed in this project because of its capability to replicate changing load conditions [15].

2.3 Inspiration for this project

Several sources inspired the work done in this project however, it would be valuable to mention that the video from J Fielding [17] was a stepping stone. This video helped design something similar to the test bench that he had created from simple inexpensive components. This was used to test unknown motors for projects involving lathes and machine tools. The most essential takeaway of the video was the arrangement of the load motor.

The majority of theoretical assistance was provided by MIT's engineering team through their informal document 'Dyno for Dummies' [18], which covered every aspect of developing a motor test dynamometer.

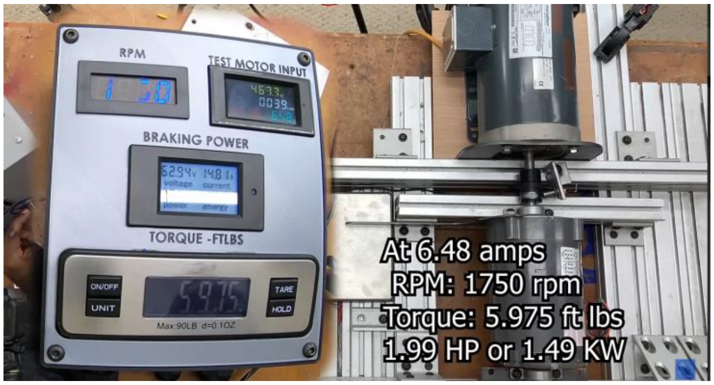


Figure 2.4:Jeremy Fielding’s dynamometer test bench setup to measure the power produced by a motor [17].

Similarly, S. Kusumba's Master's thesis at Cleveland State University detailed how to create a controlled dynamometer system [19]. This thesis explains the working of a dynamometer and various applications and use cases in the first part. Thereafter, it goes on to explain how the controls for a prototype open-loop control ‘baby dynamometer’ were designed. Their dynamometer motor was a permanent magnet DC motor and the controls were designed using a dsPIC 6010 microcontroller.

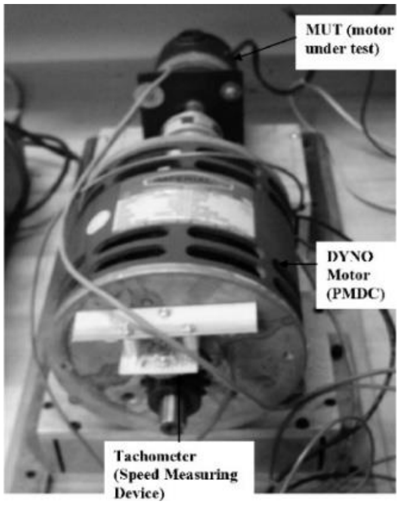


Figure 2.5: Setup of the ‘baby dynamometer’ for which the controller was developed [19].

The prototype was successfully created using numerous references from manufacturers, datasheets, and research articles. Key manufacturers, such as Yaskawa Drives, Fluke, Eaton, and Allen Bradley, provided vital insights into VFD testing and contributed to the project's testing methodology and regime. Furthermore, to improve understanding of motor drives, reference materials from publications on the subject were used. Professor S. Das's course "Fundamentals of Electric Drives" deserves special mention for its significant contribution to understanding concepts including DC dynamic braking [23].

CHAPTER 3- COMPONENT SELECTION FOR THE PROTOTYPE

3.1 Motor Under Test

For this prototype, a careful component selection was required to keep total costs down while achieving as accurate results as possible. However, most components were chosen based on their availability.

Testing VFDs is difficult for manufacturers, vendors, and operators because there are no formal recommendations or documentation available for evaluating them.

Another thing to keep in mind is that testing a VFD without running a motor is not sufficient. Some important performance tests are conducted when the motor is loaded [18]. Discussed next are the components chosen for the test bench prototype to test a 2 HP VFD Drive.

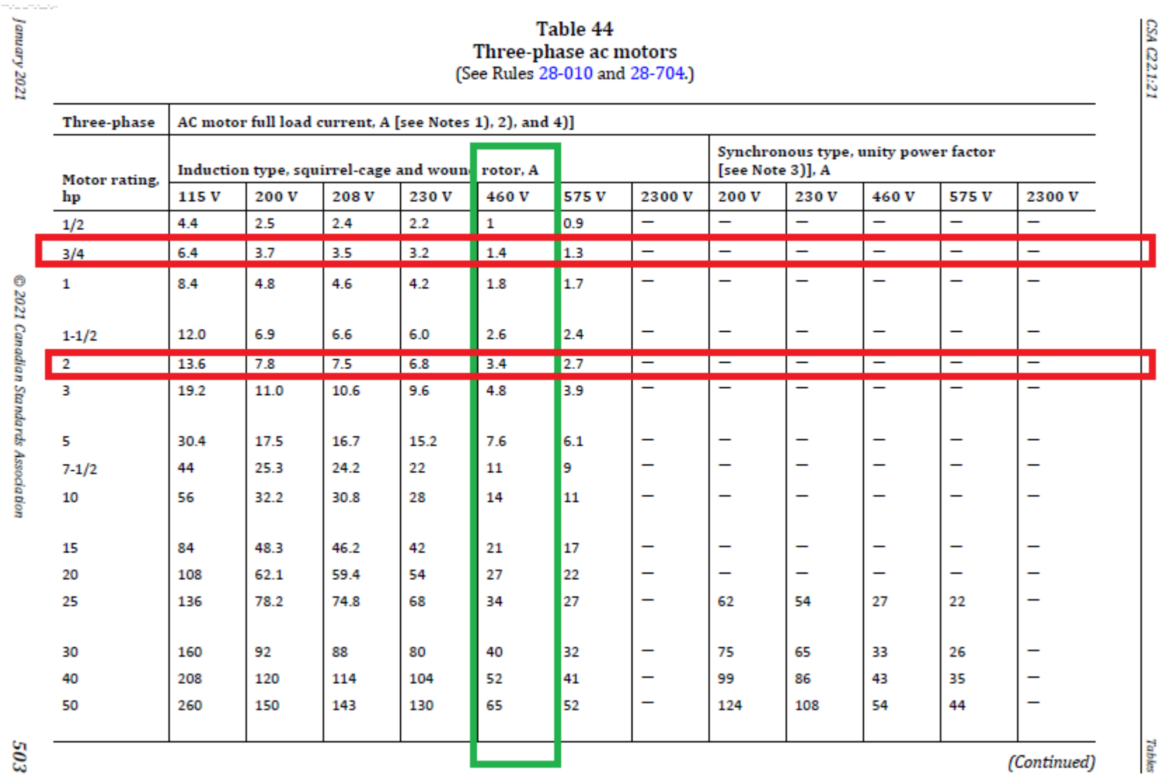
To size the motor under test for this setup, the VFD's rated output amperage must be considered. Powerflex 40 VFD (22B-E3P0N104), the 2HP (1.5kW) drive under test, has a rated output amperage of 3A at 460 V. VFDs are typically designed to meet the full load amperage demand of motors with standard wattages (VFD Cut sheet in Appendix B).

Fig 3.1 shows the Canadian Electrical Code [20] data that specifies the rated current of three-phase motors. From the figure it is found that the 2HP motor under test has a rated output current of approximately 3.4A. Industry standards call for, if possible, a VFD to be oversized (maximum up to 2 times the motor horsepower) in comparison to the motor. This is done to account for excess torque/current demand during certain points of operation like starting up or driving high inertial loads [26]. The next consideration is the minimum motor size for a given VFD.

The current limit on most VFDs can be set to one-tenth of the motor's nominal or rated current (see

Fig. 3.1). Therefore, the 2HP VFD utilized in the prototype will have a minimum current limit setting of 3A/10= 0.30A. The nameplate of the VFD under test is attached in Appendix B for related information.

For further clarity, another example of a 5 HP VFD from Eaton can be taken. This 5HP VFD will have a lower range of current limit setting of 7.6/10= 0.76 A. It can therefore be said that a VFD of 5HP would be able to control a motor that would have an FLA rating of as low as 0.76A.



January 2021

CSA C22.1:21

Table 44
Three-phase ac motors
(See Rules 28-010 and 28-704.)

Three-phase	AC motor full load current, A [see Notes 1), 2), and 4)]											
	Induction type, squirrel-cage and woun rotor, A							Synchronous type, unity power factor [see Note 3)], A				
Motor rating, hp	115 V	200 V	208 V	230 V	460 V	575 V	2300 V	200 V	230 V	460 V	575 V	2300 V
1/2	4.4	2.5	2.4	2.2	1	0.9	—	—	—	—	—	—
3/4	6.4	3.7	3.5	3.2	1.4	1.3	—	—	—	—	—	—
1	8.4	4.8	4.6	4.2	1.8	1.7	—	—	—	—	—	—
1-1/2	12.0	6.9	6.6	6.0	2.6	2.4	—	—	—	—	—	—
2	13.6	7.8	7.5	6.8	3.4	2.7	—	—	—	—	—	—
3	19.2	11.0	10.6	9.6	4.8	3.9	—	—	—	—	—	—
5	30.4	17.5	16.7	15.2	7.6	6.1	—	—	—	—	—	—
7-1/2	44	25.3	24.2	22	11	9	—	—	—	—	—	—
10	56	32.2	30.8	28	14	11	—	—	—	—	—	—
15	84	48.3	46.2	42	21	17	—	—	—	—	—	—
20	108	62.1	59.4	54	27	22	—	—	—	—	—	—
25	136	78.2	74.8	68	34	27	—	62	54	27	22	—
30	160	92	88	80	40	32	—	75	65	33	26	—
40	208	120	114	104	52	41	—	99	86	43	35	—
50	260	150	143	130	65	52	—	124	108	54	44	—

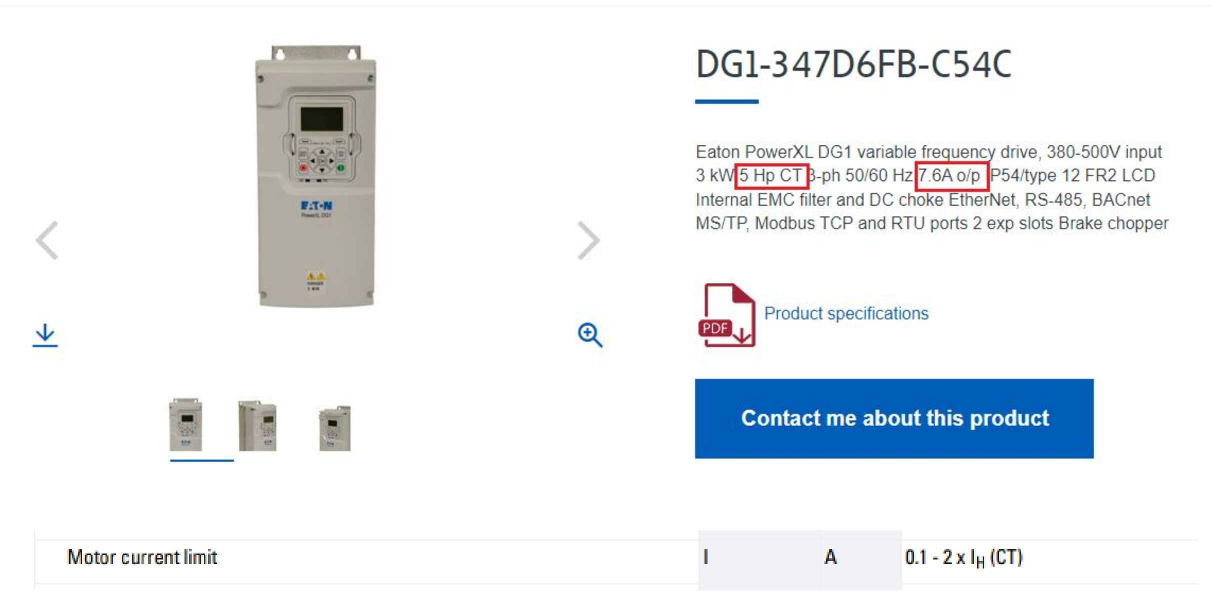
(Continued)

© 2021 Canadian Standards Association

503

Tables

Figure 3.1: Table 44 from the Canadian electrical code for determining the full load current of AC Motors. It must be noted that VFD Manufacturers tend to follow the max. output current of the VFD according to this FLA chart [20].



DG1-347D6FB-C54C

Eaton PowerXL DG1 variable frequency drive, 380-500V input 3 kW 5 Hp CT 3-ph 50/60 Hz 7.6A o/p IP54/type 12 FR2 LCD Internal EMC filter and DC choke EtherNet, RS-485, BACnet MS/TP, Modbus TCP and RTU ports 2 exp slots Brake chopper

Motor current limit	I	A	0.1 - 2 x I_H (CT)

Figure 3.2: a)An Eaton DG-1 Drive Rated at 5HP Constant Torque with a maximum current output of 7.6A. and b) Datasheet snippet showing the range of current limit setting where Ih is the high overload current for the VFD (in this case 7.6A).

Another point to consider is that an oversized VFD will not damage a smaller motor as it has inherent overload protection. This means that if the motor were to demand more current from the input, the VFD would trip with an overload fault to prevent any damage to the motor.

Therefore, to meet the current limit range and according to availability, a 0.75 HP motor having 1.4A FLA was selected. At this point, it is also crucial to mention that while testing VFDs it might not be possible to test at the rated output of the VFD. Large-size VFDs having a huge current output cannot be bench-tested at their rated currents, especially in the repair. In such cases, they are functionally tested on a smaller motor and their current transformer (CT) operation is validated. Practical constraints, testing equipment constraints and costs, may make testing VFDs at their rated current impractical. In such circumstances, testing at less than the rated current could provide enough data to assess the VFD's functioning and performance.

3.2 Load Motor Selection

The selection of a load motor is straightforward: it should be large enough to generate opposition to the motor under test. This includes accelerating the motor to maximum torque and stalling. A driving/load motor should be the same size or more powerful than the motor under test [18]. A 1.5HP motor was used for this purpose, and it produced appropriate braking torque during testing.

Now let us estimate the rated mechanical torque that this load motor can provide to the test motor.

Using (1.4):

At 1725 RPM, the torque produced by a 1.5 HP (1.1 kW) motor (load motor) will be:

$$5252 \times 1.5 = 1725 \times T_{rated}$$

$$T_{rated} = 4.57\, ft - lb = 6.20\, N - m$$

Similarly,

At 1725 RPM, the torque produced by the test motor which is 0.75HP(0.55kW) will be:

$$5252 \times 0.75 = 1725 \times T_{rated}$$

$$T_{rated} = 2.28\, ft - lb = 3.10\, N - m$$

These calculations allow us to predict how much opposing torque this load motor can generate and apply as a load to the motor under test. However, outside the scope of the current work, a load characteristic could be constructed. This load characteristic will tell us how much load the load motor is applying to the body of the motor under test at the supplied input current to the load motor.

3.3 Setup of the load motor and DC injection braking

The load motor is rated for 4.6-4.4/2.2A at 208-230/460V.

With no AC Supply to the stator of the load motor, two of the phases of the stator winding are connected to a DC Power Supply.

The load motor configuration is rather typical in this circumstance and differs from that of standard dynamometer applications. This comes with the caveat that the load motor is an AC induction motor supplied by a DC power supply. An explanation for the DC injection phenomenon is provided next.

Direct current injection into the stator creates a static magnetic field in the stator-rotor air gap. With the AC Supply disconnected, the static magnetic field resists the rotor's residual revolving magnetic field [21].

According to Lorentz's force law, the interaction of the stator's magnetic field and the induced current in the rotor produces a force that opposes the rotor's speed. This reaction generates braking torque, slowing down the rotor. According to Lenz's rule, induced current always acts in the opposite direction as the change that caused it, which means that the generated torque will resist the rotor's rotation, resulting in energy loss and slowing the system down. DC Supply is disengaged as soon as the motor RPM drops to zero [14].

However, when this DC is applied for too long after the rotor has stopped, it can potentially damage the stator windings. Therefore, the load motor must be energized only when the motor under test is running.

To estimate the braking torque produced by this process of DC injection, the following method is implemented [21]:

The slip for an induction motor is defined as:

$$s = \frac{\omega_s - \omega_r}{\omega_s} \qquad \text{……………………….(3.1)}$$

and this is a value between 0 and 1 for a motor in the ‘motoring zone’.

$\omega_s - Synchronous\ Speed\ in\ rad/s \quad \omega_r - Rotor\ Speed\ in\ rad/s$

Now given that the DC field is stationary, it can be said that the relative speed between rotor conductors and field is ω_r. Let Er be the per phase induced emf in the rotor during DC braking condition in the load motor. Induced rotor EMF(E_r) when DC is applied to the stator will be $s_b \times Er$. The reason for the direct dependence of rotor induced EMF on slip is that rotor induced voltage is proportional to the rate at which the stator field cuts the rotor conductors [23]. The same dependence holds for the frequency and reactance of the rotor and is observed in (3.3).

The DC current applied to the stator produces an equivalent stationary field to oppose the rotor motion. S_b or braking slip can be expressed as:

$$s_b = \frac{\omega_r}{\omega_s} = (1-s)\frac{\omega_s}{\omega_s} = (1-s)$$

……………………….(3.2)

Now the approximate per-phase equivalent circuit for this case can be constructed. In fig. 3.3, a typical approximate per-phase equivalent circuit of an induction motor can be seen. This uses the concept that an induction motor is a rotating transformer. In the next part of figure 3.4, a modified equivalent circuit by dividing the parameters by s_b is drawn. In the next step, the number of turns on the primary and secondary is equated and the parameters are referred to the primary side. Therefore X_r' and R' are referred reactance and resistance to the stator side respectively [23].

The expression for X_r' and R_r' and turns ratio are given by:

$$X_r' = a^2 . X_r$$

$$R_r' = a^2 . R_r$$

$$a = \frac{E}{E_r} = \frac{N_s}{N_r}$$

$$f_{eq} = (1-\mathrm{s})\mathrm{f} = s_b . \mathrm{f}$$

……………………..(3.3)

E- stator-induced EMF per phase

E_r-Per phase induced EMF of the rotor

f_{eq} – Equivalent frequency in case of braking

s_b – Slip during braking condition as defined above.

I_r - Rotor current, I_r' - Reflected current on the stator side.

R_r - Rotor Resistance per phase

X_r – Rotor Reactance/Leakage per phase

X_r '- Rotor reactance referred to the primary side

R '- Rotor resistance referred to the primary side

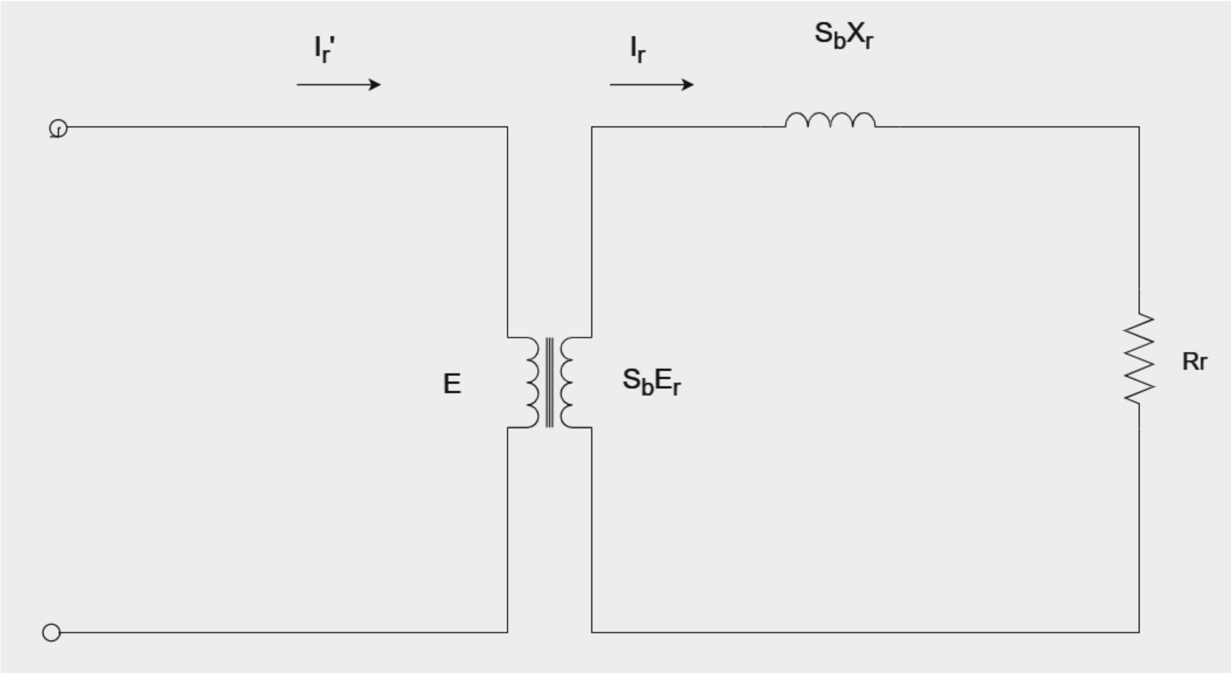


Figure 3.3: Approximate equivalent circuit for an induction machine under DC braking.

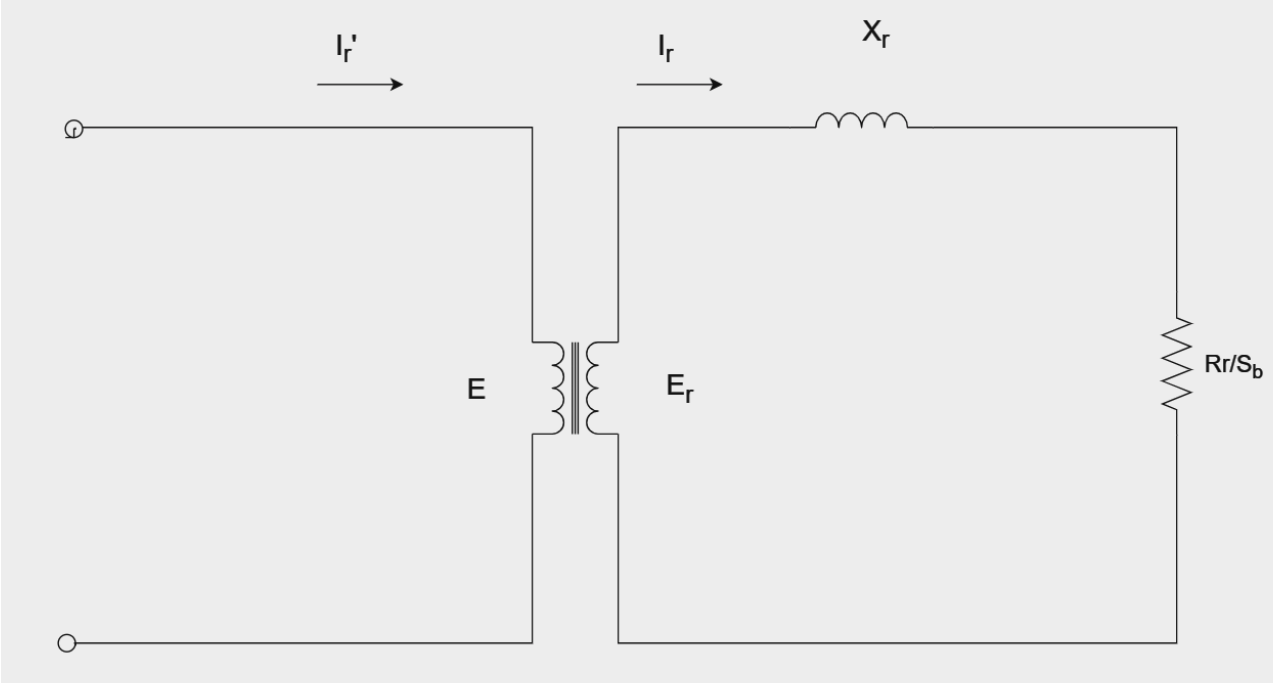


Figure 3.4: Modified equivalent circuit where the parameters on the rotor side are divided by Sb [23].

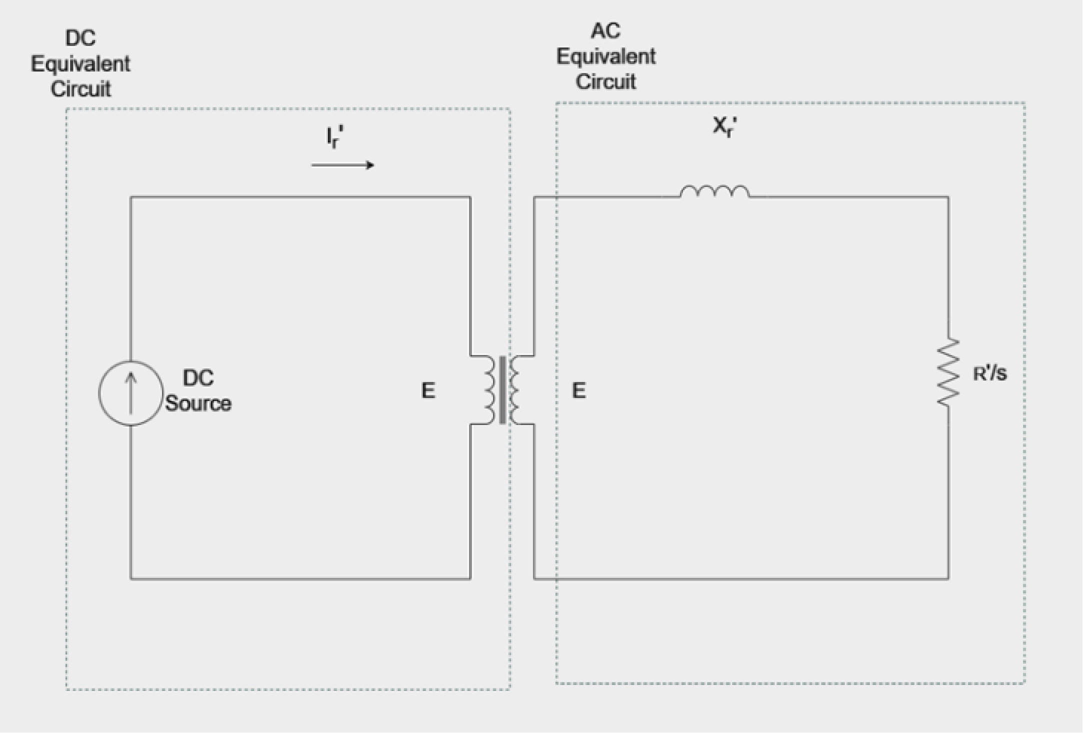


Figure 3.5: Final equivalent circuit obtained by referring the parameters to the primary side [23].

The final equivalent circuit in Fig 3.5, shows the DC source connected to the stator side. This is different from a 3-phase AC current which would supply the stator during normal operation. Therefore, the MMFs produced by the DC side and the AC side can be equated in this case. This is done to find out the DC current I_d shown in fig 3.5 in terms of the stator current (I_s).

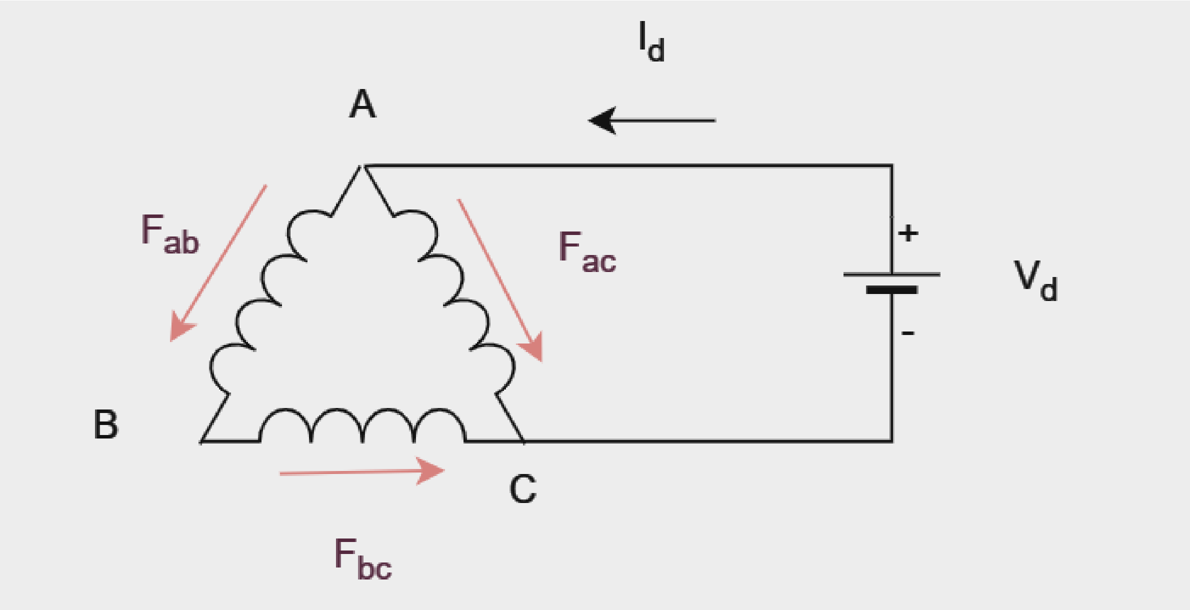


Figure 3.6: Two lead connections of DC Supply to the stator of an induction motor. Red arrows represent the MMF developed in each phase.

To clarify, the 2-lead delta connection has been considered and analyzed. This is because the prototype has the motor connected in delta and two leads connected to the DC supply as shown above in figure 3.6.

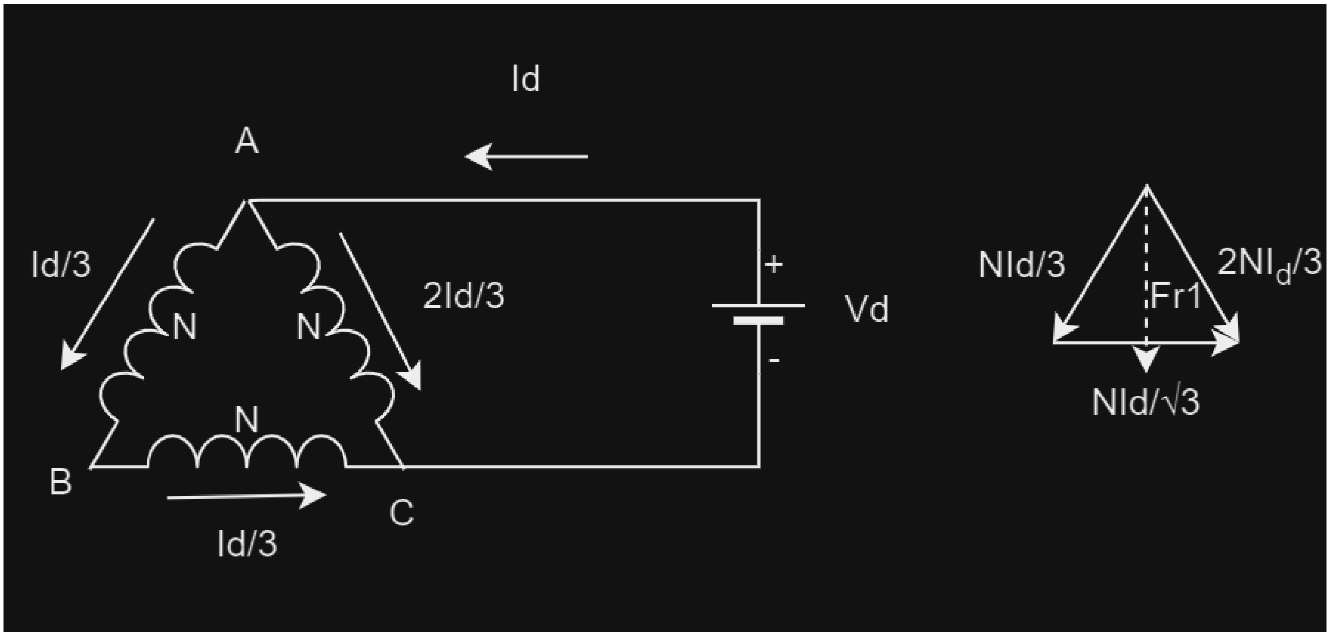


Figure 3.7: Circuit used to realize the MMF produced by each phase of the delta winding when connected to a DC Supply and its corresponding vector diagram on the right.

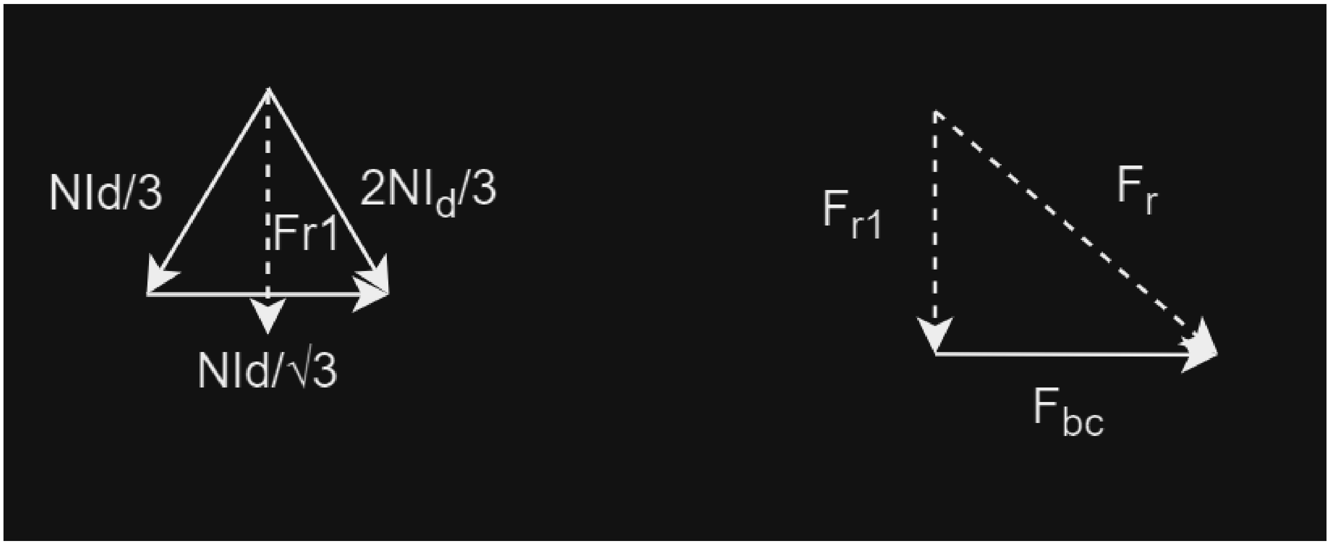


Figure 3.8: The three vectors are added to find the resultant vector Fr in two steps. The three vectors are added to find the resultant vector Fr in two steps. Fr1 = Fab + Fac and Fr = Fbc + Fr1

Using Figure 3.8, the resultant MMF vector F_r was calculated for this particular 2-lead delta configuration. Calculations were done using the assumption that each of the winding has 'N' number of turns and has the equal winding resistance. 'N' or 'N_s' refers to the number of stator turns.

$$MMF = No. of\ turns\ per\ phase\ \times I_{ph}(per\ phase\ current) \qquad \text{…...…………….(3.4)}$$

Here F_r is the vector sum of the three vectors of the MMF produced by each of the three-phase windings.

$$\overrightarrow{F_r} = \overrightarrow{F_{ab}} + \overrightarrow{F_{ac}} + \overrightarrow{F_{bc}} \qquad \text{………………….(3.5)}$$

$$\overrightarrow{F_{r1}} = \sqrt{(F_{ab})^2 + (F_{ac})^2} \qquad \text{……………….(3.6)}$$

$$\overrightarrow{F_r} = \sqrt{((F_{r1})^2 + (F_{bc})^2)} \qquad \text{……………….(3.7)}$$

Using the above equations, the value of the MMF produced by the DC part of the circuit can be found. The next step is to equate the AC equivalent peak value of MMF to the component of MMF produced by DC. The direction of the vector F_r is the same as the direction of the MMF vector F_{ac} .This gives us a relationship between stator current I_s and applied DC current I_d. This calculation would be different for each of the configurations shown in figure 3.10.

$$|F_r|(magnitude) = N_s \times I_s(or\ I_d) \qquad \text{………………(3.8)}$$

(3.8) is the general equation for the mmf (magnetomotive force) measured in ampere-turns (At). Here N_s is the number of stator turns and I_s, is the stator current. In the case of DC injection braking, the stator current can be replaced by I_d, the applied DC current.

$$F_s = Peak\ value\ of\ MMF\ in\ the\ AC\ circuit$$

$$= \frac{3}{2}.N_s.(I_s.\sqrt{2}) \qquad \text{………………….(3.9)}$$

On equating MMFs the following is obtained:

$$N_s \times I_d = \frac{3}{2} \times N_s \times I_s \times \sqrt{2}$$

…………………(3.10)

which gives:

$$I_s = \frac{\sqrt{2}}{3} \times I_d$$

……………………(3.11)

The current I_s , is the *AC equivalent current* produced in the stator by the DC source creating an opposing braking torque T_{eb} at the rotor. To calculate this, the torque equation of a three-phase induction motor being applied with a three-phase AC supply is used. From equivalent circuit in figure 3.5 and using the torque equation will give:

$$T_{eb} = \frac{3}{\omega s} \times \mathrm{I}_r'^2 \times \frac{R_r'}{S_b} = \frac{\frac{3}{\omega s} \times I_s^2}{\left(\frac{Rr'}{S_b}\right)^2 + (X_r')^2} \times \frac{R_r}{S_b}$$

……..……………(3.12)

On substituting I_s from (3.11) into the equation above, a torque characteristic like the one below in figure 3.9 will be obtained.

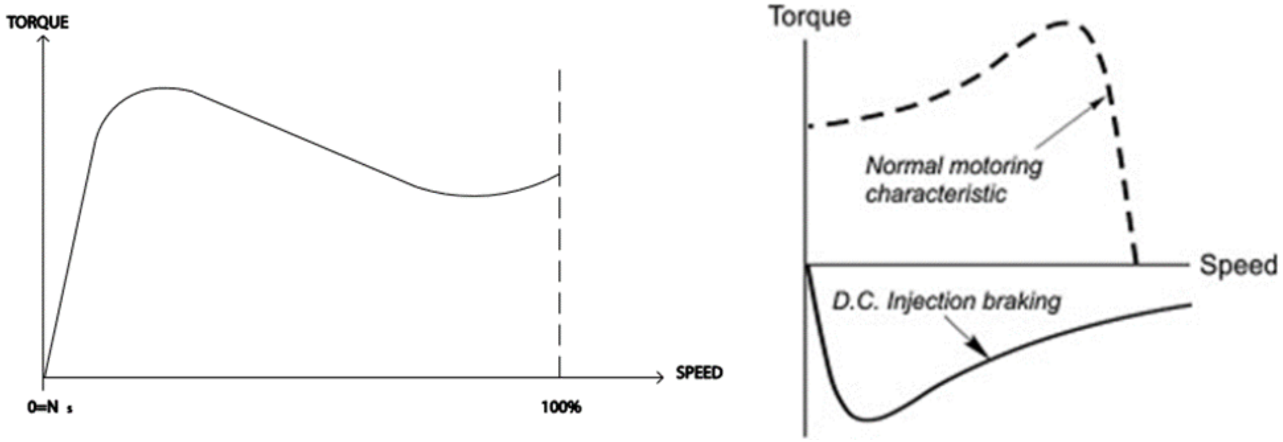


Figure 3.9: Curves showing the relationship between braking torque and speed during DC Injection Braking [25][14].

Table 3.1 : DC injection configurations and voltage developed across stator windings.

Configuration	**I_s-Stator Current**	**I_d = External DC applied**	**R_q=Resistance**	**V_d=I_d*R_1**
2 Lead **Star(D)**	$\sqrt{\frac{2}{3}}.I_d$	$\sqrt{\frac{3}{2}}.I_s$	$2.R_1$	$2.\sqrt{\frac{3}{2}}.I_s.R_1$= 2.45*$V_1$
3 Lead **Star(C)**	$\frac{\sqrt{2}}{2}.I_d$	$\sqrt{2}.I_s$	$\frac{3}{2}.R_1$	$\frac{3}{\sqrt{2}}.I_s.R_1$= 2.12*$V_1$
2 Lead **Delta(B)**	$\frac{\sqrt{2}}{3}.I_d$	$\frac{3}{\sqrt{2}}.I_s$	$\frac{2}{3}.R_1$	$\sqrt{2}.I_s.R_1$=1.414*V_1
3 Lead **Delta(A)**	$\frac{2\sqrt{2}}{3}.I_d$	$\frac{3}{2\sqrt{2}}.I_s$	$3.R_1$	$\frac{3}{2}.\frac{3}{\sqrt{2}}.I_s.R_1$=3.18*$V_1$

It can be noted from the above table that star configuration sees lesser equivalent resistance in this case. Therefore, the current Id is higher. Star configuration(D) or configuration B for delta is used in most cases of DC Injection braking [21]. In this case, connection B was used for the motor windings with the application of DC on 2 windings. This configuration provides the maximum amount of Id or external DC current applied to the stator during the DC injection operation.

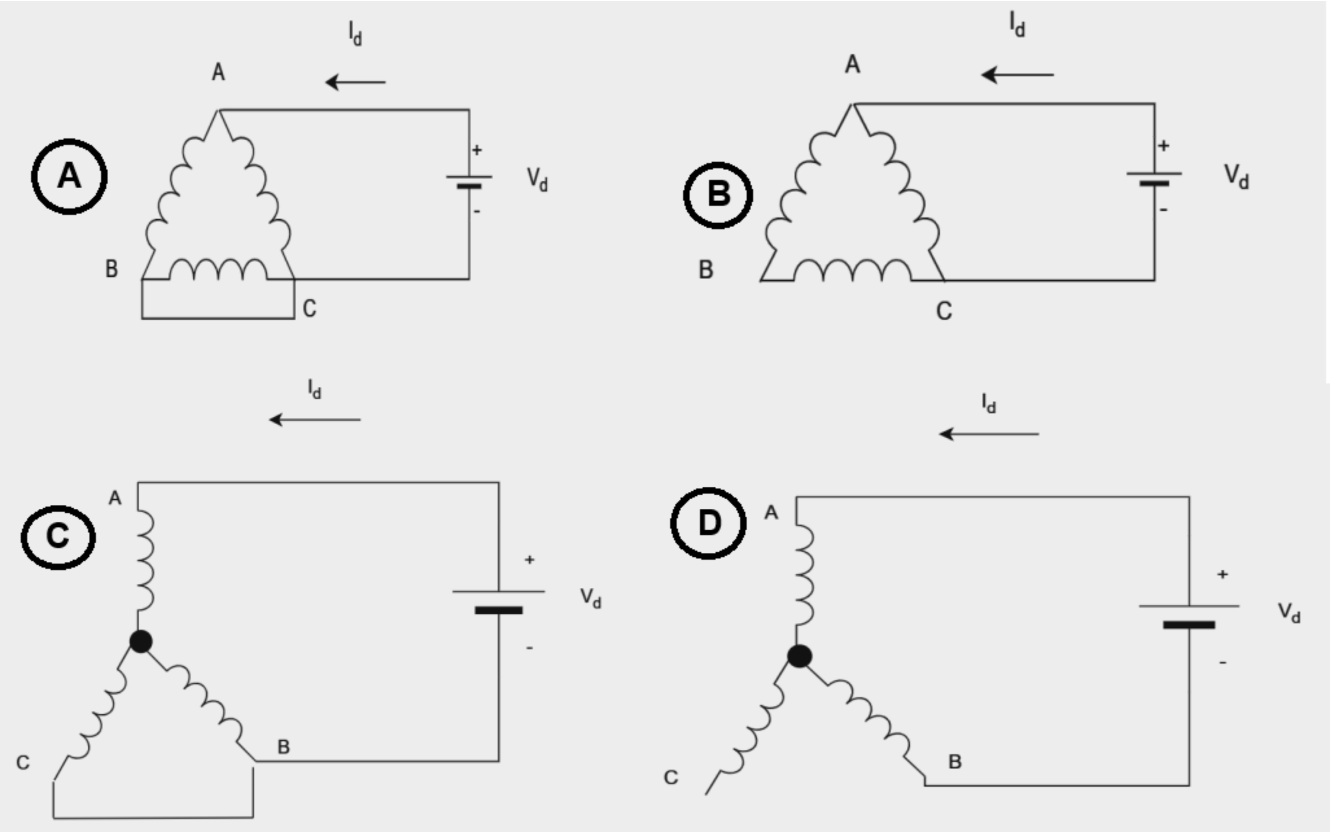


Figure 3.10: The stator connection types for DC injection braking. The most common ones are (B) and (D) [14].

The DC supply for braking the motor can be applied using the configurations shown in figure 3.10. Configurations A and C are both three lead configurations whereas B and D are two lead configurations .

Braking torque is directly dependent on the square of the stator current ie. I_s^2 and depends inversely on the rotor reactance which changes with the frequency (3.12). This also verifies the claim by the motor manufacturer SAF Drives [24] discussed below.

There are certain rules specified by motor and VFD manufacturers for applying DC Current to the motor [25]:

1. DC Current (I_{dc}) applied can be 2-4 times the rated current of the motor.
2. Time to brake (brake timing) is inversely proportional to $(I_{dc})^2$ which means that the more the amount of current injected into the stator, the more the braking torque and quicker the stop.

Therefore, it is clear that the more the amount of current supplied to the stator windings, the more braking torque applied in opposition and the faster the motor will come to a stop [25].

In this project setup, the amount of current applied has always been kept lower than the rated current for the load motor due to the limitations of the power supply. The connections of the actual prototype are shown below from the concept CAD drawing for this model.

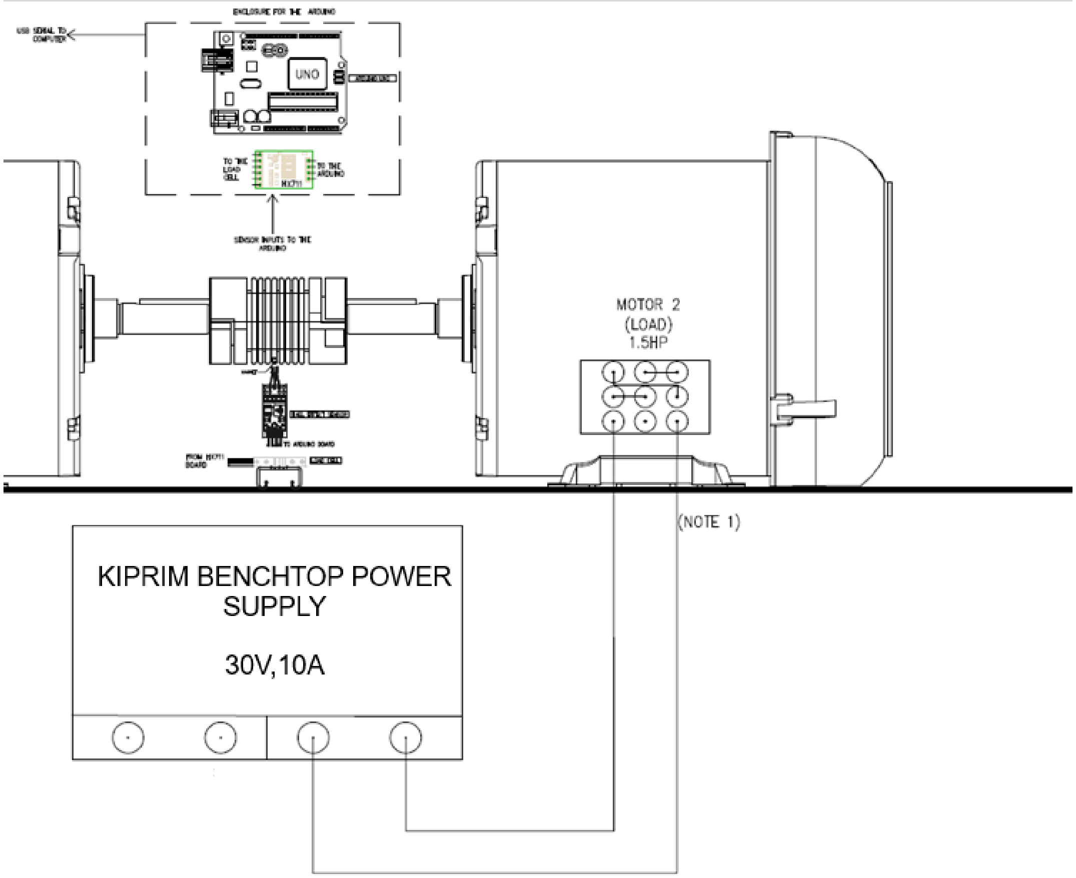


Figure 3.11: Snippet from the concept drawing showing the actual connections in the prototype setup [Appendix B].

3.4 VFD under test

The initial test of this prototype was performed on a Variable Frequency Drive that had been in service for about 10 years and had undergone multiple repairs during its lifetime. The Allen Bradley VFD utilized in the project was satisfactorily fixed in the shop but did not receive much testing afterward. This is a common occurrence, so it was decided to put up a motor test bench to aid test the VFDs post-repair This would ensure that they remained dependable in the field.

3.5 Controller and sensor setup

An Arduino UNO was chosen in this prototype to easily program and interface the sensors. Also due to previous experience with Arduino, it proved to be a good choice.

The setup of the two sensing elements- the hall effect sensor and the load cell will now be discussed. The hall effect sensor is mounted on the coupling shaft of the two motors. It works on the principle that whenever a magnet's north pole comes close to its top face, a 'low' digital signal to the controller is transmitted.

The load cell uses a strain gauge connected as a balanced Wheatstone bridge that helps to convert the force applied into voltage (a few millivolts signal) which is conditioned internally to output a weight. This load cell helps us find the mass of the body applying that force. In this setup, a torque arm is extended from the body of the load motor, and the force of that is applied directly onto the load cell. A calibration is done before testing which does a tare, unit, and offset adjustment so that the measurements are accurate. The length of the torque arm is fixed to 30 cm and the torque is computed as given below.

$$Torque(N-m) = Force(N) * Perpendicular\ distance(fixed\ at\ 0.30m)$$

$$Force = mass(in\ Kg) * acceleration(in\ this\ case\ is\ accn.due\ to\ gravity\ 'g')$$

$$and\ g = 9.81 m/s^2$$

$$Torque(N-m) = m(from\ load\ cell) * 9.81 * 0.30$$

…………………(2.4)

Please note that the calculated torque would be referred to as instantaneous mechanical torque at the motor shaft. Other ways of calculating this torque could be using the product of inertia and acceleration. This would apply to motors with a known rotor moment of inertia and the ability to determine the acceleration of the load.

Table 3.2: The components used in the test bench prototype are summarized.

Component	**Specification**	**Relevance/Functionality**
1. Motor Under Test(MUT)	Baldor Motor BM3112 3ph, 208-230/460VAC,0.75HP,1.5A FLA	Acts as the motor under load that is regulated by the VFD.
2. Load/Driver Motor	General Electric K257 Series 3PH, 208-230/460VAC,1.5 HP,4.7-4.4/2.2A FLA	This motor acts as a load in opposition to the MUT and can be used to simulate different loading conditions.
3. VFD 22B-E3P0N104	PowerFlex 40 Series 460-600VAC, 2HP, Output 3A FLA,4.5A Overload Amps with HIM Keypad.	Controls the speed of the motor under test by varying the frequency.
4. Measurement Unit	Fluke Clamp-on Current Meter	Meters are used to measure the line side current draw, and VFD output voltage/current.

5. HIM for VFD	Human Interface machine display	Used as an extension of the VFD display and for monitoring and changing its parameters.
6. Arduino with LCD Disp.	Arduino UNO with LCD module	Used for measuring the speed and torque by acquiring sensor input, performing calculations and displaying real-time data.
7. Programmable Benchtop DC PSU	KIPRIM DC Power Supply Unit-30V,10A	Used to apply DC Current across any 2 phases of the load motor for DC Injection Braking [17]
8. PC for Data Acquisition	Arduino Serial Port Monitor	Used a Python script to acquire data from the serial port and store it in MS Excel for further processing.
8. Hall Effect Sensor used for RPM Measurement	A3144e based hall effect sensor	The sensor gets activated as soon as a magnetic pole is brought in the vicinity of this sensor.
9. Load Cell for Torque Measurement	HX711 Load Cell for Kitchen Scale	This load cell senses the amount of weight being put on the scale using strain gauge technique.
10. Misc. Components	Transformer(80VA,120/480V), Mechanical Frame, Motor Coupler, Struts, Lever Arm (Trimmed to 30cm), Weights for calibration.	-

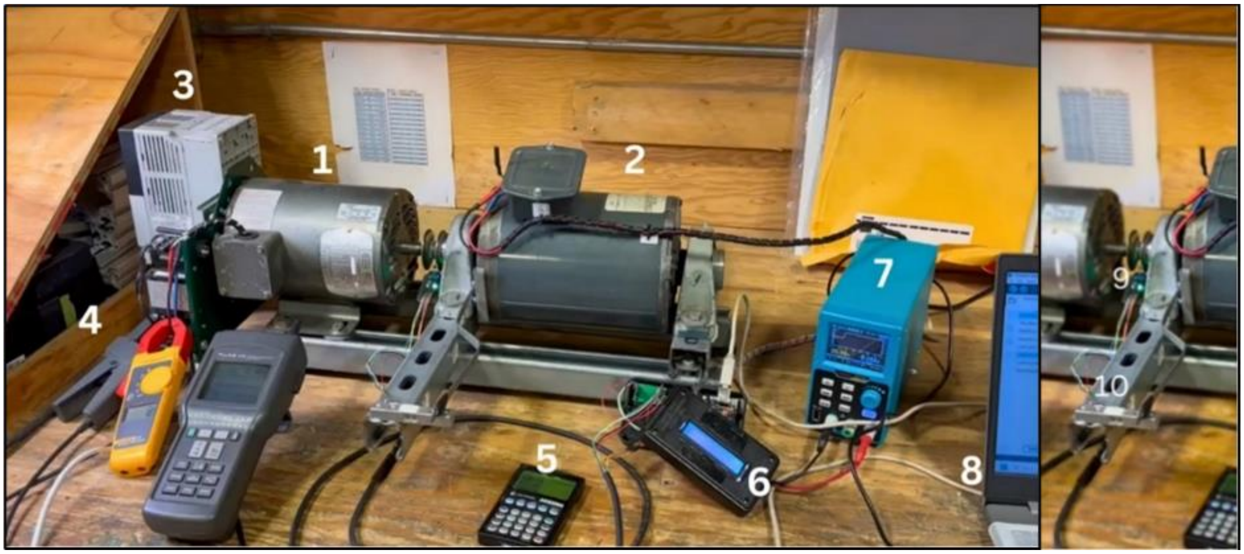


Figure 3.12: A physical prototype for a motor drive test bench at KJ Controls repair department

3.6 Recommended safety equipment and testing precautions

During the VFD prototype testing in a controlled work environment, the operator was prioritised. When the motors were in operation, safety glasses were worn, and the testing area was cordoned off. However, it should be emphasised that the prototype is still missing some critical safety measures that are recommended for future designs.

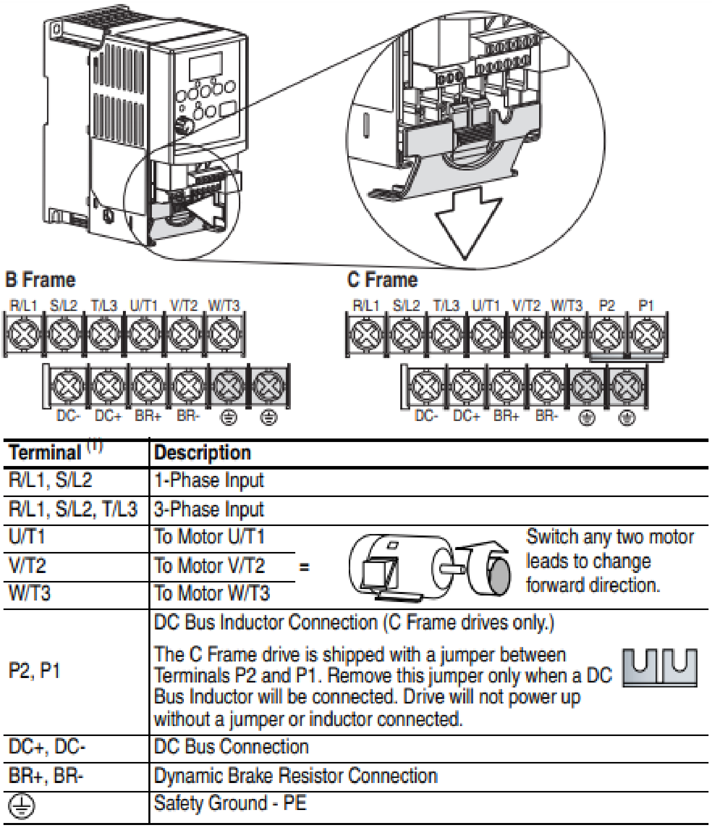
Some safety equipment that could be added in future design would be:

1. Emergency stop button and safety alarms: Required for instantly stopping the test in the event of a visible failure of test bench components.
2. Impact suppression fiberglass guard- intended to reduce the impact caused by flying debris from moving motor parts.
3. Overcurrent protection- there should be overcurrent protection on the line side of the VFD.

CHAPTER 4- VFD TESTING PROTOTYPE OUTCOMES

4.1 Results for Test 1- Static Test

Before starting this test, it is imperative to ensure that the VFD is turned off and the filter capacitors are discharged fully. If not, they must be discharged again and the voltage across them must be tested after 4-5 minutes (standard according to CSA [20]). All the terminals referred to in this section are shown in the figure below for clarity.



Terminal (1)	Description	
R/L1, S/L2	1-Phase Input	
R/L1, S/L2, T/L3	3-Phase Input	
U/T1	To Motor U/T1	= Switch any two motor leads to change forward direction.
V/T2	To Motor V/T2	
W/T3	To Motor W/T3	
P2, P1	DC Bus Inductor Connection (C Frame drives only.) The C Frame drive is shipped with a jumper between Terminals P2 and P1. Remove this jumper only when a DC Bus Inductor will be connected. Drive will not power up without a jumper or inductor connected.	
DC+, DC-	DC Bus Connection	
BR+, BR-	Dynamic Brake Resistor Connection	
⏚	Safety Ground - PE	

Figure 4.1: The power wiring terminals showing the location of the test leads of the multimeter would probe (Frame B) [10]

Next, with the power off, the diodes and transistors must be inspected and the forward voltage across them must be observed. To complete this test the following table from chapter 2 was filled out. These results are from the test sheet filled out post-repair. All the values are healthy and within the specified range.

Table 4.1: Steps for Static Testing of VFDs

Step	**(+) Positive Multimeter Lead**	**(-) Negative Multimeter Lead**	**Tested/Measured Value**
1	(-)Terminal	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	0.485-0.489 Vdc across each
2	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	(-)Terminal	OL
3	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	(+) Terminal	0.485-0.492Vdc across each
4	(+) Terminal	R(L1),S(L2),T(L3), U(T1),V(T2),W(T3) Terminals	OL
5	Brake Terminal 1	Brake Terminal 2	OL(No dynamic brake installed)
6	Brake Terminal 2	Brake Terminal 1	0.51Vdc (No dynamic brake installed)

Part 2 of the static test is where the power is applied to the input terminals of the drive and the values of the DC Bus are taken. At this time, the DC bus voltage is measured at the DC+, and DC- Terminals. For this drive, at startup, the DC bus value was measured at 671VDC. This was lower than the expected 678VDC. Also, during operation at load, the DC bus values were in the range of 380VDC-525 V which were lower than the expected 678V assuming a constant 480V supply. The variation could be caused due to faulty capacitors or a voltage sag in the input line voltage. With the aging of capacitors, the effective internal series resistance increases which can cause irregular drops in voltage. This has been added to the FAT sheet as a deficiency for further inspection.

4.2 Stall Test on Motor with Stress Trip Verification

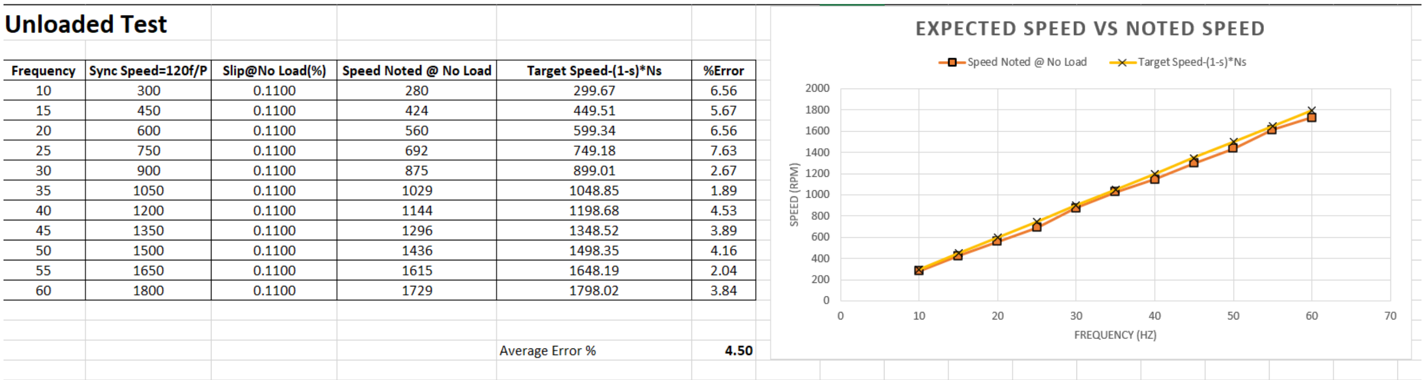
The stall test is a stress test used to find out if the current limit overload trip function on the VFD works. These values for current will not be accurate and might be slightly high at the moment of tripping.

Table 4.2: Tabulated results from Stress Trip Test.

Test motor freq (Hz)	**Motor speed (RPM)**	**Torque just before stalling(N-m)**	**Current Drawn by Motor(A)**	**Power output by the system (W)**	**Stress trip Y/N**
10Hz	288	1.25	1.27	37.68	Y
15Hz	408	1.05	0.93	44.83	Y

As a part of this test, a stress trip was done by keeping the stalled motor running for up to 60 seconds. It tripped with a current limit fault(P033) and detected an overload. This ensures the VFD is stress tested and can trip in an overload condition. This verified the VFD's overload protection functionality successfully.

4.3 Free Run Test



Unloaded Test

Frequency	Sync Speed=120f/P	Slip@No Load(%)	Speed Noted @ No Load	Target Speed-(1-s)*Ns	%Error
10	300	0.1100	280	299.67	6.56
15	450	0.1100	424	449.51	5.67
20	600	0.1100	560	599.34	6.56
25	750	0.1100	692	749.18	7.63
30	900	0.1100	875	899.01	2.67
35	1050	0.1100	1029	1048.85	1.89
40	1200	0.1100	1144	1198.68	4.53
45	1350	0.1100	1296	1348.52	3.89
50	1500	0.1100	1436	1498.35	4.16
55	1650	0.1100	1615	1648.19	2.04
60	1800	0.1100	1729	1798.02	3.84
				Average Error %	**4.50**

Figure 4.2: Free run test to check VFD functionality

For the free run test, the motor is run at no load/lightly loaded condition and the VFD is used to control the motor speed. Two expressions that help in calculating N_s and N_r :

$$Ns(Synchronous\ Speed) = (120 * frequency)/(number\ of\ poles)$$

$$Nr(Rotor\ Speed) = (1 - s) \times N_s$$

The expression for N_r or rotor speed is used to calculate the expected or target speed of the motor. The slip at no load is negligible and can be calculated from the expression below:

$$Slip(s) = \frac{N_s - N_r}{N_s} \times 100\ (\%)$$

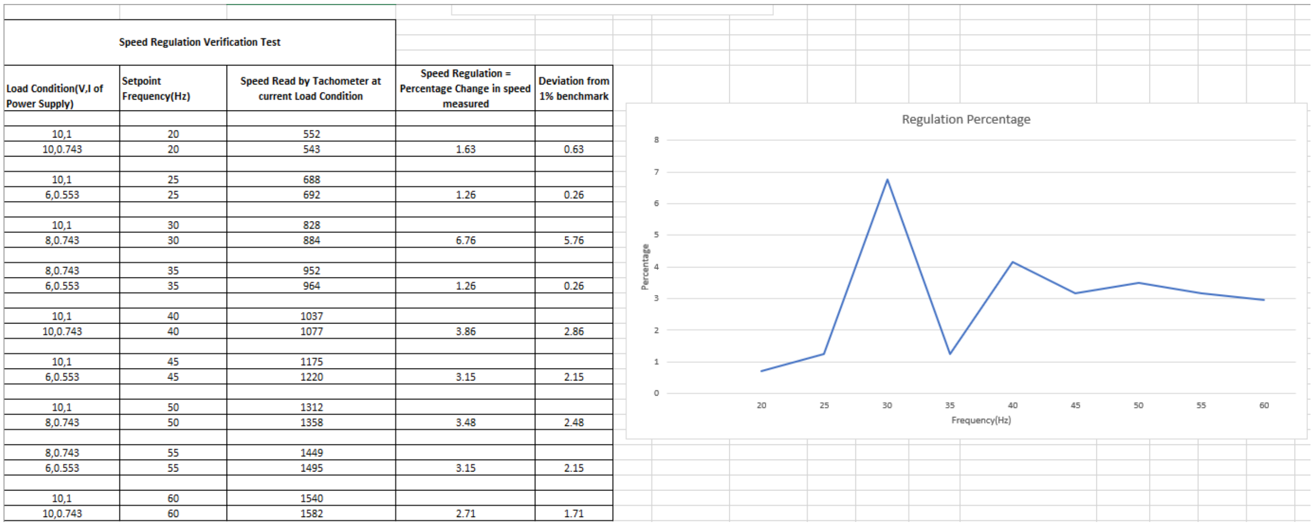
From the motor characteristics curve (Appendix B), it can be seen that the speed at no-load is 1798 RPM. This slip is the result of the motor providing mechanical power to overcome friction and windage losses (constant losses) at no-load operation.

A plot between expected and obtained speeds is obtained. Results show a correlation between expected and noted speed confirming the VFD's functionality. The average error % between the expected and actual speed is 4.50%.

The variance in no-load speed can be attributed to factors, including internal VFD parameter settings such as inaccurate slip compensation, supply voltage fluctuations, issues with DC bus voltage stability, and slight mechanical resistance within the motor. Notably, the large difference between target speed and noted speed at rated frequency is major and must be investigated. Slip has been considered as a constant for the no-load section of the test, despite small variations caused by changes in the motor's core losses. This consideration could add to the discrepancy between the set and achieved speeds. A note has been made to investigate the speed inconsistencies in the checklist.

Tachometer measurements confirmed ±5 RPM accuracy at speeds up to 750 RPM. Further investigation of the Hall effect RPM measurement accuracy is recommended before designing any future test setups.

4.4 Load Test and Speed Regulation Test



Speed Regulation Verification Test

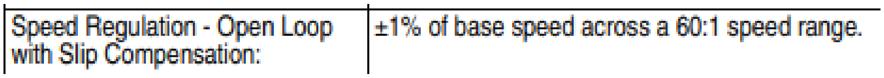
Load Condition(V,I of Power Supply)	Setpoint Frequency(Hz)	Speed Read by Tachometer at current Load Condition	Speed Regulation = Percentage Change in speed measured	Deviation from 1% benchmark
10,1	20	552		
10,0.743	20	543	1.63	0.63
10,1	25	688		
6,0.553	25	692	1.26	0.26
10,1	30	828		
8,0.743	30	884	6.76	5.76
8,0.743	35	952		
6,0.553	35	964	1.26	0.26
10,1	40	1037		
10,0.743	40	1077	3.86	2.86
10,1	45	1175		
6,0.553	45	1220	3.15	2.15
10,1	50	1312		
8,0.743	50	1358	3.48	2.48
8,0.743	55	1449		
6,0.553	55	1495	3.15	2.15
10,1	60	1540		
10,0.743	60	1582	2.71	1.71

Figure 4.3: Speed Regulation Test for VFDs

Most VFDs have a speed regulation value defined in their datasheets which is the percentage change in speed measured with the change of load at a constant frequency setpoint.

The load on the motor was reduced slightly at each setpoint frequency and a slight fluctuation in the speed was seen. The recorded values show a percentage change in speed when the load was dropped. The VFD under test is unable to keep up with the speed regulation benchmark of 1% as can be seen in the plot. Additionally, this VFD can control slip compensation that compensates for the inherent slip in an induction motor. This frequency is added to the commanded output frequency based on motor current [10]. Its default value is set to 2 Hz, however, this aspect was not investigated or taken into consideration. Parameter A114 from the advanced program mode would need to be varied for varying or obtaining the current setting of slip compensation.

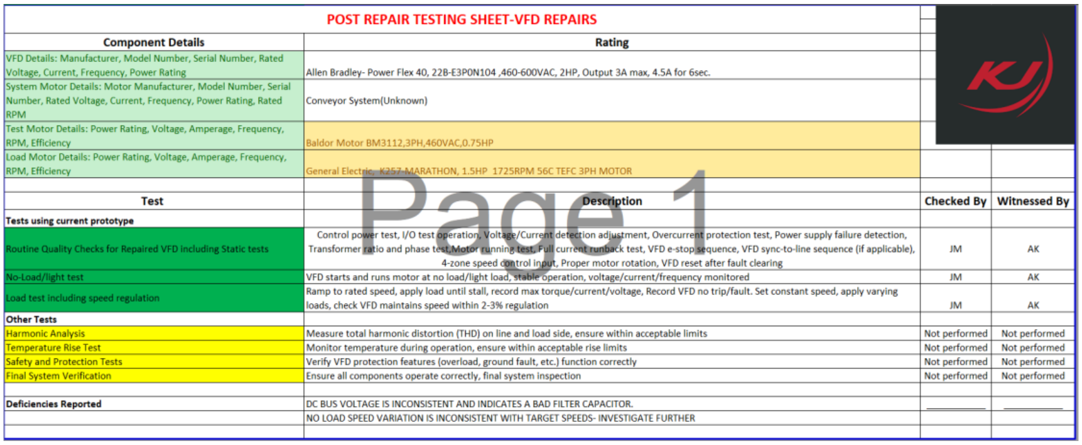
Figure 4.4 shows a snippet from the datasheet of the VFD being tested. It can be inferred that the drive is able to regulate speed such that it stays within 1% of the desired setpoint. Also, the speed range is between rated speed and 1/60th of rated speed. This type of drive typically senses the change in load by monitoring the change in load current drawn by the motor [10].



Speed Regulation - Open Loop with Slip Compensation:	±1% of base speed across a 60:1 speed range.

Figure 4.4: The expected value of speed regulation from the VFD manual [10].

4.5 Proposed VFD testing checklist



POST REPAIR TESTING SHEET-VFD REPAIRS

Component Details	Rating		
VFD Details: Manufacturer, Model Number, Serial Number, Rated Voltage, Current, Frequency, Power Rating	Allen Bradley- Power Flex 40, 22B-E3P0N104 ,460-600VAC, 2HP, Output 3A max, 4.5A for 6sec.		
System Motor Details: Motor Manufacturer, Model Number, Serial Number, Rated Voltage, Current, Frequency, Power Rating, Rated RPM	Conveyor System(Unknown)		
Test Motor Details: Power Rating, Voltage, Amperage, Frequency, RPM, Efficiency	Baldor Motor BM3112,3PH,460VAC,0.75HP		
Load Motor Details: Power Rating, Voltage, Amperage, Frequency, RPM, Efficiency	General Electric, K257-MARATHON, 1.5HP 1725RPM 56C TEFC 3PH MOTOR		
Test	**Description**	**Checked By**	**Witnessed By**
Tests using current prototype			
Routine Quality Checks for Repaired VFD including Static tests	Control power test, I/O test operation, Voltage/Current detection adjustment, Overcurrent protection test, Power supply failure detection, Transformer ratio and phase test,Motor running test, Full current runback test, VFD e-stop sequence, VFD sync-to-line sequence (if applicable), 4-zone speed control input, Proper motor rotation, VFD reset after fault clearing	JM	AK
No-Load/light test	VFD starts and runs motor at no load/light load, stable operation, voltage/current/frequency monitored	JM	AK
Load test including speed regulation	Ramp to rated speed, apply load until stall, record max torque/current/voltage, Record VFD no trip/fault. Set constant speed, apply varying loads, check VFD maintains speed within 2-3% regulation	JM	AK
Other Tests			
Harmonic Analysis	Measure total harmonic distortion (THD) on line and load side, ensure within acceptable limits	Not performed	Not performed
Temperature Rise Test	Monitor temperature during operation, ensure within acceptable rise limits	Not performed	Not performed
Safety and Protection Tests	Verify VFD protection features (overload, ground fault, etc.) function correctly	Not performed	Not performed
Final System Verification	Ensure all components operate correctly, final system inspection	Not performed	Not performed
Deficiencies Reported	DC BUS VOLTAGE IS INCONSISTENT AND INDICATES A BAD FILTER CAPACITOR.	___________	___________
	NO LOAD SPEED VARIATION IS INCONSISTENT WITH TARGET SPEEDS- INVESTIGATE FURTHER		

Figure 4.5: The testing checklist proposed for VFD Testing (Performed tests in green) [Appendix B]

A VFD testing procedure sheet has been formulated which acts as a checklist for the tests mentioned above. Additional tests that act as routine quality checks have also been listed for the repair technician to reference A standard format of a testing checklist has been prepared with editable comments, signatures, and testing notes field.

4.6 Economical Aspects

The adoption of an in-house Variable Frequency Drive testing system will transform how the repairs department handles VFD repair jobs. Rather than outsourcing testing services, which causes time delays of up to 2 or more weeks, they can now conduct load testing at their facilities. This change will not only streamline the operations but also result in significant cost savings.

For the cost of the prototype to be recovered, it would take a maximum of 2-3 months in the scenario where around 5 drives are tested a month. In cases of a contract with an industry to test several drives at once or over a few weeks, this time gap can be narrowed even further. However, for achieving the level of the outsourcing option, additional equipment would have to be procured that might cost up to $15,000. One of the major expenses would be to procure a drive analyser that would be able to study the harmonics produced by the drive in detail. This would set back the payback period close to 3 years given that at least 5 drives are tested each month.

Another value addition this would bring would be to the estimating department. When estimating a repair job, the team would have a better idea of the time and man-hours required for testing. The KJ shop rates have been obtained from the repair department’s estimating team and the outsourcing rates are from a company specializing in VFD repairs and testing [4]. Average freight shipping costs have been applied as per KJ’s logistics.

The table below shows a cost-time analysis of the VFD testing procedure being done in-house vs being outsourced. The savings per drive tested come out to be $80 which would be the minimum savings.

Table 4.3: Cost-Time Analysis of VFD Testing (Outsourcing vs Workshop)

Category	**Outsourcing Option**	**Testing In-House Option**
Lead Times	5-14 Days (1-3 Days for shipping)	4-5 Hours of Testing (2 People)
Mean hourly rate	$80/hr worked	$95(Shop rate)
Total Hours required	Varies based on complexity (4-8 hours)	4 Hours
Total Cost (Average 8 hours)	$80 * 8 = $640	$95*4*2(8 Man-hours) = $760
Shipping Cost (Estimate each way)	$100	$0
Total Costs Incurred	640+200=$840	$760
Estimated Savings	-	≃$80/ per drive tested. (~9.58%)
Estimated Delivery Time	16 Days (±2 Days)	4-5 hours (±2 hours)
Future prototype setup cost (Estimated)	$0	$15000 (inclusive of drive analyser costs)
Estimated time to recover all costs (Payback period)	-	30-36 Months (Considering there are about 5 drive repaired/month)

For the tests outsourced, there are some tests that might not be feasible to be replicated in the repair shop working environment. Also, the unavailability of certain expensive equipment like a drive analyser increases the initial setup costs greatly, sample results from such an equipment are shown below.

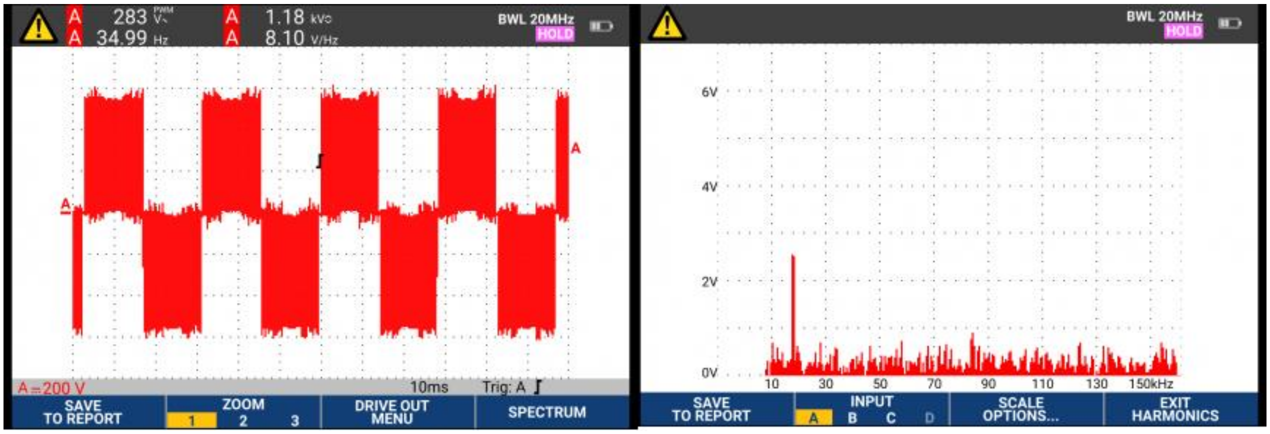


Figure 4.6: A drive analyzer is able to provide reliable results for motor-drive systems [27]

CHAPTER 5- CONCLUSION AND FUTURE WORK

5.1 Conclusion

The prototype served as a foundation for future development of a more robust and dependable test bench. This prototype helped clarify the concept of DC dynamic braking and how it may be used in this application. Furthermore, the operation of the dynamometer was promising, facilitating the loading of the motor.

The capabilities of the prototype are summarized below:

1. The test prototype was able to test a 2 HP VFD having a 3A output.
2. Real time monitoring of motor speed and torque while under load.
3. Load simulation provided the ability to conduct functionality and performance tests.

The prototype fell short in some areas, but with a few modifications, it may be improved, as described below:

1. The VFD could only be tested at a partially loaded condition using this setup.
2. The platform experiences unwanted vibrations and instability.
3. This design does not include certain safety features like an emergency stop button (E-Stop).
4. Lack of precise control of load torque and inability to set different loading profiles.
5. No cooling mechanism for the loading motor/dynamometer.

5.2 Extending the physical implementation

While the test prototype will be examined further in the future with various types of motors, its accuracy will be assessed. A possible example would be the hall effect sensor(s), which would be positioned on at least two axes of the shaft. Multiple sensors offer greater precision at faster speeds. The other choice would be to increase the motor base's stability to eliminate vibration. Work must be done to ensure the safety of this equipment. This test equipment should be enclosed or covered to keep moving components from flying away at high speeds. Overcurrent protection for the motors should be supplied by a circuit breaker rated at 1.25 times the FLA of the test motor(s). Warning labels would also be appropriately placed on this equipment [20].

This customizable power supply supports serial communication with a PC. Data logging is another important component if this system is used frequently, and a Data Acquisition device, such as the National Instruments DAQ, would be an excellent choice.

Furthermore, a more robust system will be designed, which will include a control panel with a PLC for motor control. This will also incorporate a closed loop torque control that will be able to simulate different load conditions/profiles on the motor being driven.

5.3 Use of regeneration to reduce energy consumption during testing

While functioning as a brake to simulate a loaded condition for the motor under test, the load motor creates energy that is dissipated as heat. In future physical realizations for motor testing, implementing regeneration of energy lost during braking would be a worthwhile endeavour. In this situation, the AC power produced during the generating phase might be inverted and stored in batteries or supplied back into the power source. In principle, the motor being tested would use only enough power to compensate for the losses [18].

References and Bibliography

[1] Eaton Corporation., “How to choose between a soft starter and a variable frequency drive?”, 2013.

[2] W. J. Weber, “Engineering Fundamentals of Multi-MW Variable Frequency Drives-How They Work, Basic Types, And Application Considerations,” in Proceedings of the 31st Turbomachinery Symposium, 2002.

[3] TMEIC (R&D for Mitsubishi Drives), “Medium voltage variable frequency drives acceptance testing,” 2012.

[4] Radwell, “Radwell repair services (Canada),” Radwell.ca. [Online]. Available: https://www.radwell.ca/en-CA/Services/Repair.

[5] S. Rouse, “Variable frequency drives - An Energy Efficiency Reference Guide by Natural Resources Canada,” 2009.

[6] Electrical Technology, “What is a VFD (Variable Frequency Drive) – Circuit, Working, Types & Applications,” ELECTRICAL TECHNOLOGY, 14-Nov-2021. [Online]. Available: https://www.electricaltechnology.org/2021/11/vfd-variable-frequency-drive.html.

[7] Yokogawa Drives, “Electrical Motor and Variable Speed Drive Testing: A 4-Step Process for Testing Motor and Drive Systems,” May 2020.

[8] IEEE, “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,” 2022.

[9] J. Bullick and B. Wilkinson, “Applying harmonic filters to VFDs to meet the IEEE 519 specification,” Kebamerica.com. [Online]. Available: https://www.kebamerica.com/wp-content/uploads/2020/03/KEB-Whitepaper-Applying-harmonic-filters-for-VFD-applications.pdf.

[10] Allen Bradley, “PowerFlex 40 Adjustable Frequency AC Drive User Manual.”,2020.

[11] B. Sam, “KJ Controls - PowerFlex Testing Procedure Guide,” 2022.

[12] Magtrol Inc, “Dynamometer DSP 6000 Series,” Magtrol.com. [Online]. Available: https://www.magtrol.com/wp-content/uploads/dsp6001.pdf.

[13] “KJ controls & contracting,” KJ Controls LTD. [Online]. Available: https://kjcontracting.net/.

[14] C. Somers, C. Moussa, and K. Al-Haddad, “Emergency DC injection braking system,” in 2015 IEEE International Conference on Industrial Technology (ICIT), 2015.

[15] Wikipedia contributors, “Dynamometer,” Wikipedia, The Free Encyclopedia, [Online]. Available: https://en.wikipedia.org/w/index.php?title=Dynamometer&oldid=1221164556.

[16] “Dynamometer: What is it? How does it work? Types, uses,” Iqsdirectory.com. [Online]. Available: https://www.iqsdirectory.com/articles/dynamometers.html.

[17] J. Fielding, “How to measure Horsepower for any electric motor: (#077),” 24-Feb-2020. [Online]. Available: https://www.youtube.com/watch?v=1Pd0lUKWe7o.

[18] A. M. Spring and M. B. R. Lab, “A brief, informal introduction to motor testing,” Mit.edu. [Online]. Available: https://evt.mit.edu/textbooks/Dynos_for_Dummies.pdf.

[19] S. Kusumba, “DYNAMOMETER PROPORTIONAL LOAD CONTROL,” Cleveland State University, 2004.

[20] Canadian Standards Association, Toronto, Canada, Jan. 2023, Canadian Electrical Code, Part I Safety Standard for Electrical Installations; CSA C22.1:23, 2023.

[21] V. Vodovozov, Electric drive systems and operation, Bookboon, 2019.

[22] “Input diode and output transistor check procedure on a VFD,” Yaskawa.com. [Online]. Available: https://solutioncenter.yaskawa.com/selfservice/viewContent.do?externalId=11185&sliceId=1.

[23] Das and NPTEL-IIT-K, “Analysis of DC Dynamic Braking of an induction motor,” 2019.

[24] S. Rouse, “SAF Drives-DC Injection Braking- Installation and Operation,” 2017.

[25] MTE Limited, “Powerbrake-DCB4- DC Injection braking unit (Product Documentation),” 2006.

[26] “Oversized VFD,” Vfds.in. [Online]. Available: http://www.vfds.in/oversized-vfd-684146.html.

[27] Fluke, “How to measure output voltage from a VFD to a motor,” Fluke.com, 01-Apr-2019. [Online]. Available: https://www.fluke.com/en-ca/learn/blog/motors-drives-pumps-compressors/how-to-measure-output-voltage-from-a-vfd-to-a-motor.

Appendix A

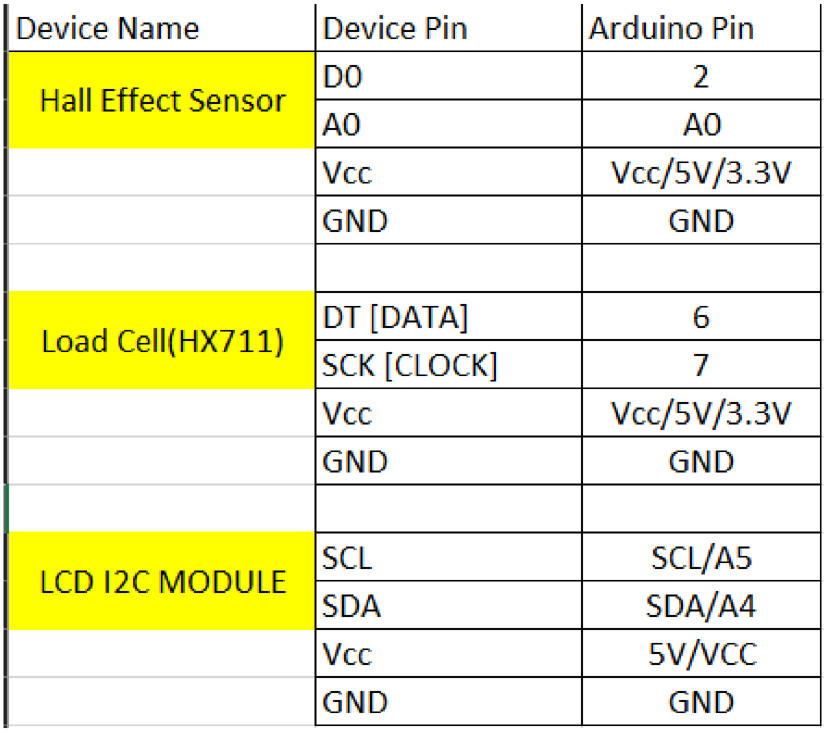
Arduino Code

This code is used to interface the strain gauge load cell and hall-effect sensor in the prototype to compute torque (in N-m) and speed (in RPM).

```
#include "HX711.h"

//variables for hall sensor
volatile double full_revolutions = 0;
volatile double rpm = 0;
volatile long timeold = 0;
//variables for hall sensor end

//Torque scale variables
HX711 scale;
uint8_t dataPin = 6;
uint8_t clockPin = 7;
float T;

void setup() {
  Serial.begin(115200); //Setting the baud rate to 115200
  Serial.println();

  //Configuring the hall sensor interrupt
  attachInterrupt(2,hall_fall, FALLING);

  scale.begin(dataPin, clockPin);
  Serial.print("UNITS: ");

  //average of 10 raw readings taken by load cell
  Serial.println(scale.get_units(10));


  //Scale Calibration Process to be run before every new test

  Serial.println("\nEmpty the scale, press a key to continue");
  while (!Serial.available())
    ;
  while (Serial.available())
  Serial.read();

  scale.tare(); //clears scale and any offset value

  Serial.println("\nPut 10 grams on the scale, press a key to continue");


  //flush any serial input
```

```
  while (Serial.available())
  Serial.read();
  delay(2500);

  scale.calibrate_scale(10, 5);//Calibrating with 10 gram weight
  Serial.print("UNITS: ");
  Serial.println(scale.get_units(10));

  Serial.println("\nScale is calibrated, press a key to continue");
  Serial.println(scale.get_scale());
  Serial.println(scale.get_offset());
  while (!Serial.available())
    ;
  while (Serial.available()) Serial.read();
}

void loop() {
  if (scale.is_ready()) {
    Serial.print("UNITS: ");
    float W = scale.get_units(100);//Average of 100 raw readings
    //Change to a lower no. of raw readings for faster performance
    Serial.println(W);
    //Torque calculation
    float D = 0.30;
    float g = 9.81;
    T = (W / 1000) * g * D;
    Serial.println("The torque measured at the shaft is: ");
    Serial.println(T);
    delay(500);
  }

  //RPM Meter using hall sensor
  // Starts reading RPM only after 10 full revs are completed.
if (full_revolutions >= 10) {
     rpm = 60*1000/(millis() - timeold)*full_revolutions;
  //60*1000 is done to convert from milliseconds to minutes
     timeold = millis();//updating time since last interrupt
     full_revolutions = 0;
     Serial.print("RPM:");
     Serial.println(rpm);
   }
}

void hall_fall()
 {
   full_revolutions++;
 }
```

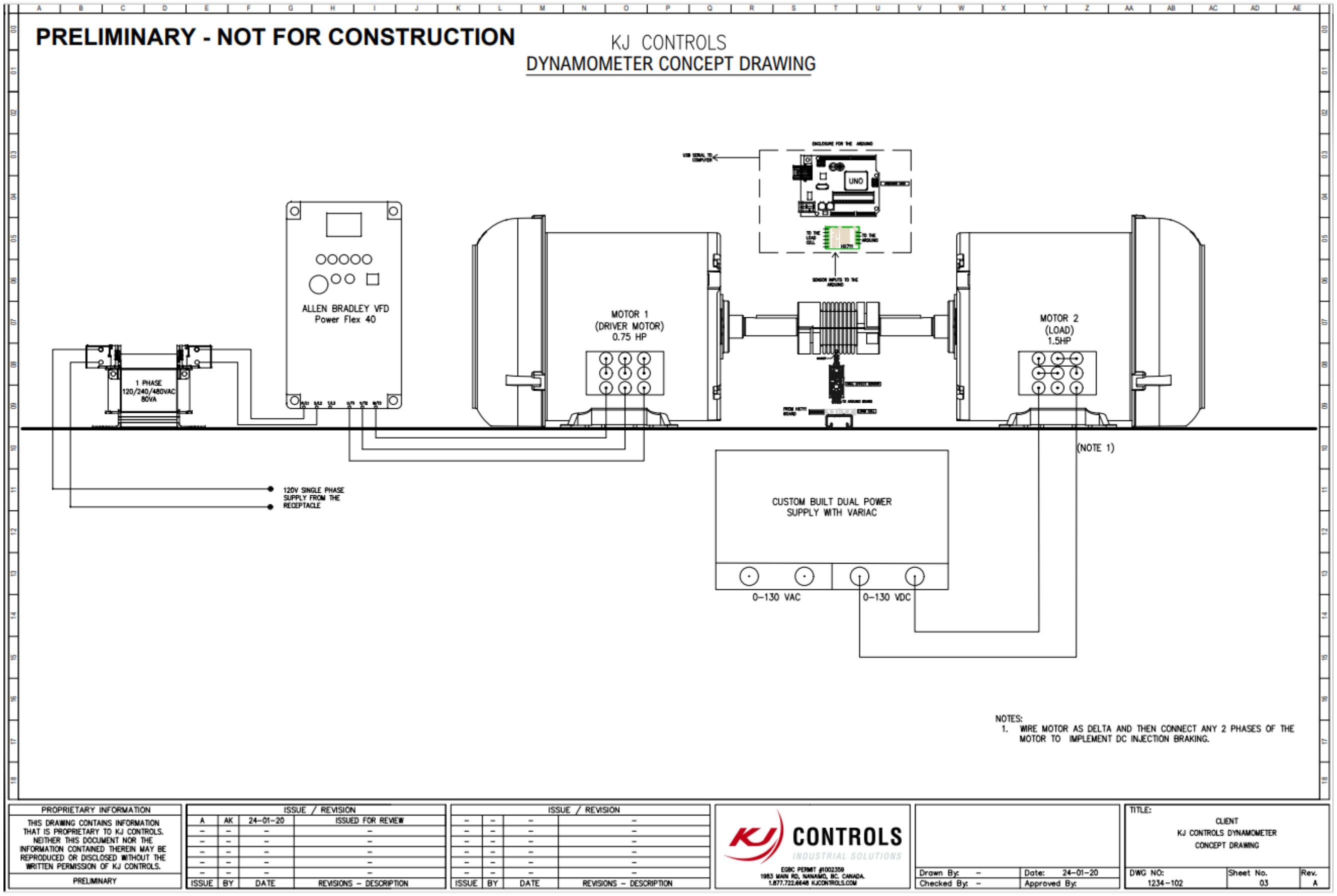
Arduino Connections



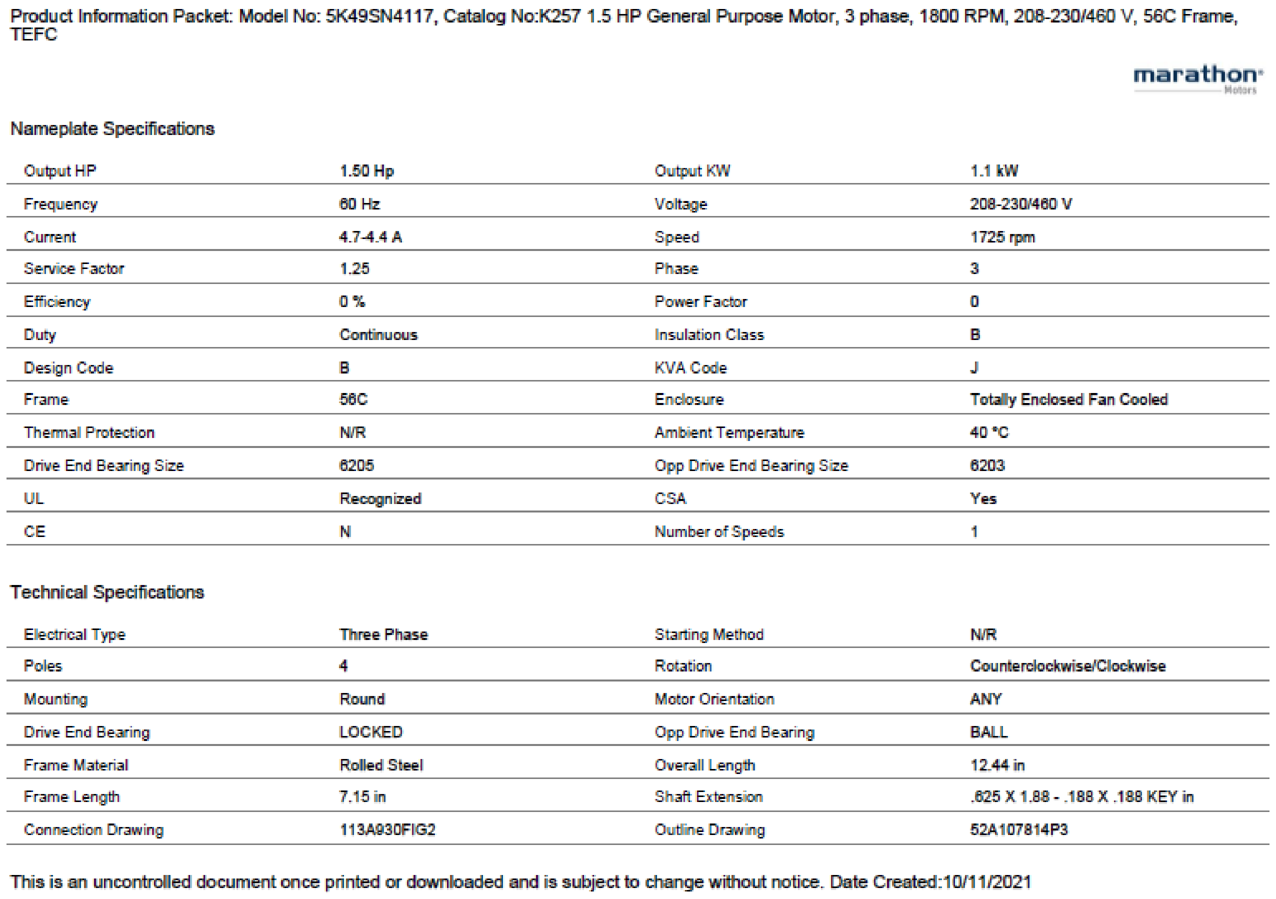
Device Name	Device Pin	Arduino Pin
Hall Effect Sensor	D0	2
	A0	A0
	Vcc	Vcc/5V/3.3V
	GND	GND
Load Cell(HX711)	DT [DATA]	6
	SCK [CLOCK]	7
	Vcc	Vcc/5V/3.3V
	GND	GND
LCD I2C MODULE	SCL	SCL/A5
	SDA	SDA/A4
	Vcc	5V/VCC
	GND	GND

Appendix B

Design Layout in AUTOCAD



Load Motor Data Sheet



Product Information Packet: Model No: 5K49SN4117, Catalog No:K257 1.5 HP General Purpose Motor, 3 phase, 1800 RPM, 208-230/460 V, 56C Frame, TEFC

Nameplate Specifications

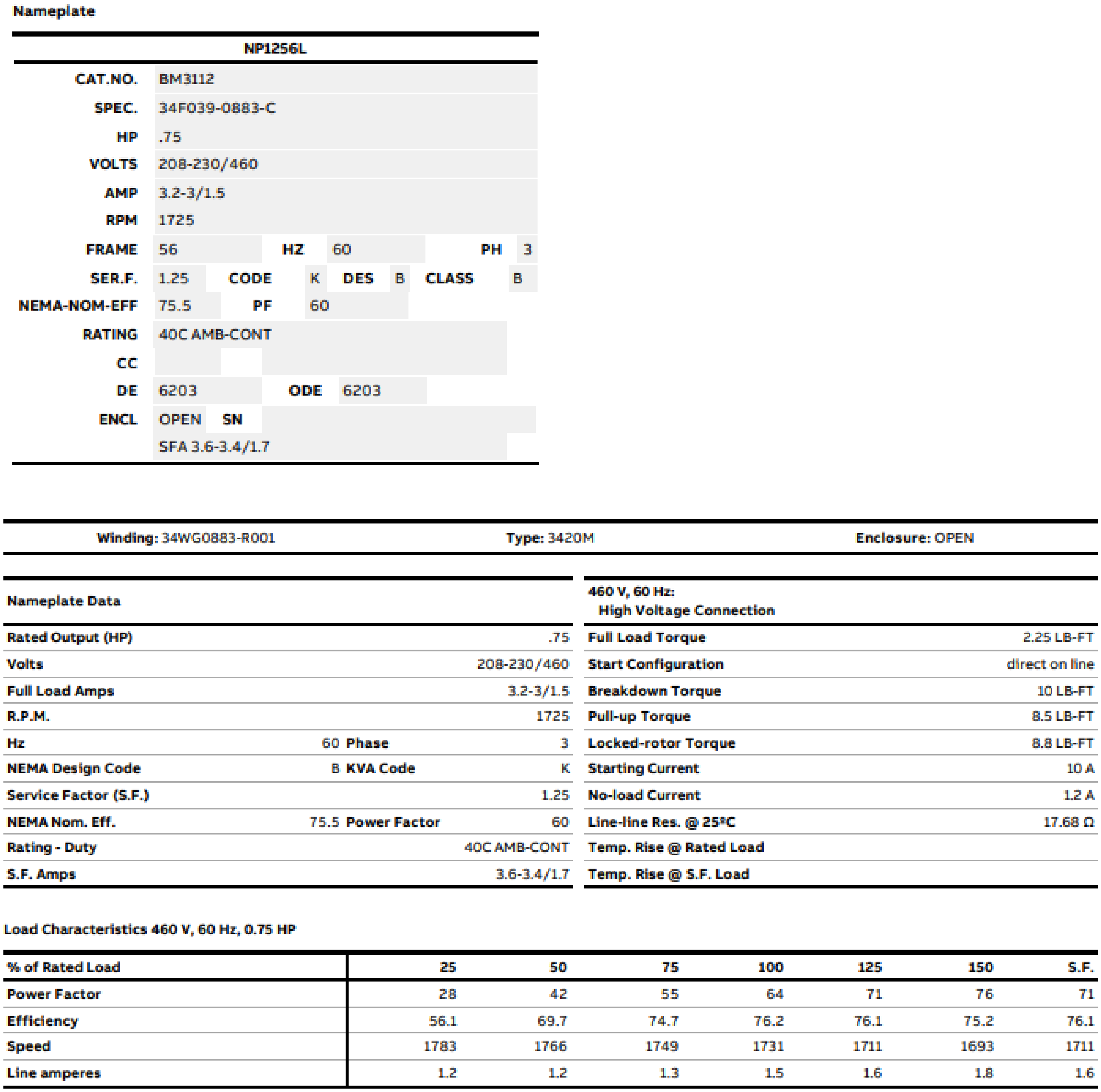
Output HP	1.50 Hp	Output KW	1.1 kW
Frequency	60 Hz	Voltage	208-230/460 V
Current	4.7-4.4 A	Speed	1725 rpm
Service Factor	1.25	Phase	3
Efficiency	0 %	Power Factor	0
Duty	Continuous	Insulation Class	B
Design Code	B	KVA Code	J
Frame	56C	Enclosure	Totally Enclosed Fan Cooled
Thermal Protection	N/R	Ambient Temperature	40 °C
Drive End Bearing Size	6205	Opp Drive End Bearing Size	6203
UL	Recognized	CSA	Yes
CE	N	Number of Speeds	1

Technical Specifications

Electrical Type	Three Phase	Starting Method	N/R
Poles	4	Rotation	Counterclockwise/Clockwise
Mounting	Round	Motor Orientation	ANY
Drive End Bearing	LOCKED	Opp Drive End Bearing	BALL
Frame Material	Rolled Steel	Overall Length	12.44 in
Frame Length	7.15 in	Shaft Extension	.625 X 1.88 - .188 X .188 KEY in
Connection Drawing	113A930FIG2	Outline Drawing	52A107814P3

This is an uncontrolled document once printed or downloaded and is subject to change without notice. Date Created:10/11/2021

Motor Under Test Datasheet



Nameplate

NP1256L							
CAT.NO.	BM3112						
SPEC.	34F039-0883-C						
HP	.75						
VOLTS	208-230/460						
AMP	3.2-3/1.5						
RPM	1725						
FRAME	56	HZ	60	PH	3		
SER.F.	1.25	CODE	K	DES	B	CLASS	B
NEMA-NOM-EFF	75.5	PF	60				
RATING	40C AMB-CONT						
CC							
DE	6203	ODE	6203				
ENCL	OPEN	SN					
	SFA 3.6-3.4/1.7						

Winding: 34WG0883-R001 **Type:** 3420M **Enclosure:** OPEN

Nameplate Data			
Rated Output (HP)			.75
Volts			208-230/460
Full Load Amps			3.2-3/1.5
R.P.M.			1725
Hz	60	Phase	3
NEMA Design Code	B	KVA Code	K
Service Factor (S.F.)			1.25
NEMA Nom. Eff.	75.5	Power Factor	60
Rating - Duty			40C AMB-CONT
S.F. Amps			3.6-3.4/1.7

460 V, 60 Hz: High Voltage Connection	
Full Load Torque	2.25 LB-FT
Start Configuration	direct on line
Breakdown Torque	10 LB-FT
Pull-up Torque	8.5 LB-FT
Locked-rotor Torque	8.8 LB-FT
Starting Current	10 A
No-load Current	1.2 A
Line-line Res. @ 25ºC	17.68 Ω
Temp. Rise @ Rated Load	
Temp. Rise @ S.F. Load	

Load Characteristics 460 V, 60 Hz, 0.75 HP

% of Rated Load	25	50	75	100	125	150	S.F.
Power Factor	28	42	55	64	71	76	71
Efficiency	56.1	69.7	74.7	76.2	76.1	75.2	76.1
Speed	1783	1766	1749	1731	1711	1693	1711
Line amperes	1.2	1.2	1.3	1.5	1.6	1.8	1.6

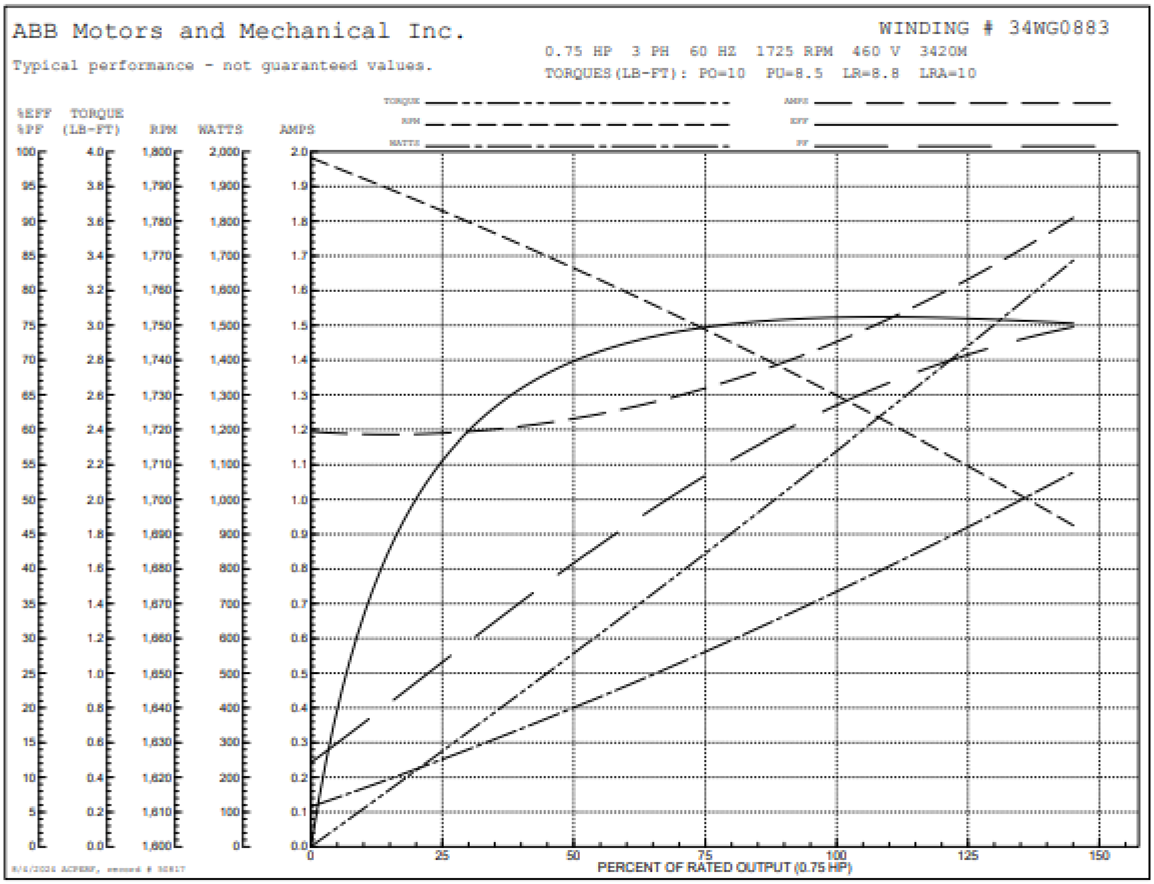
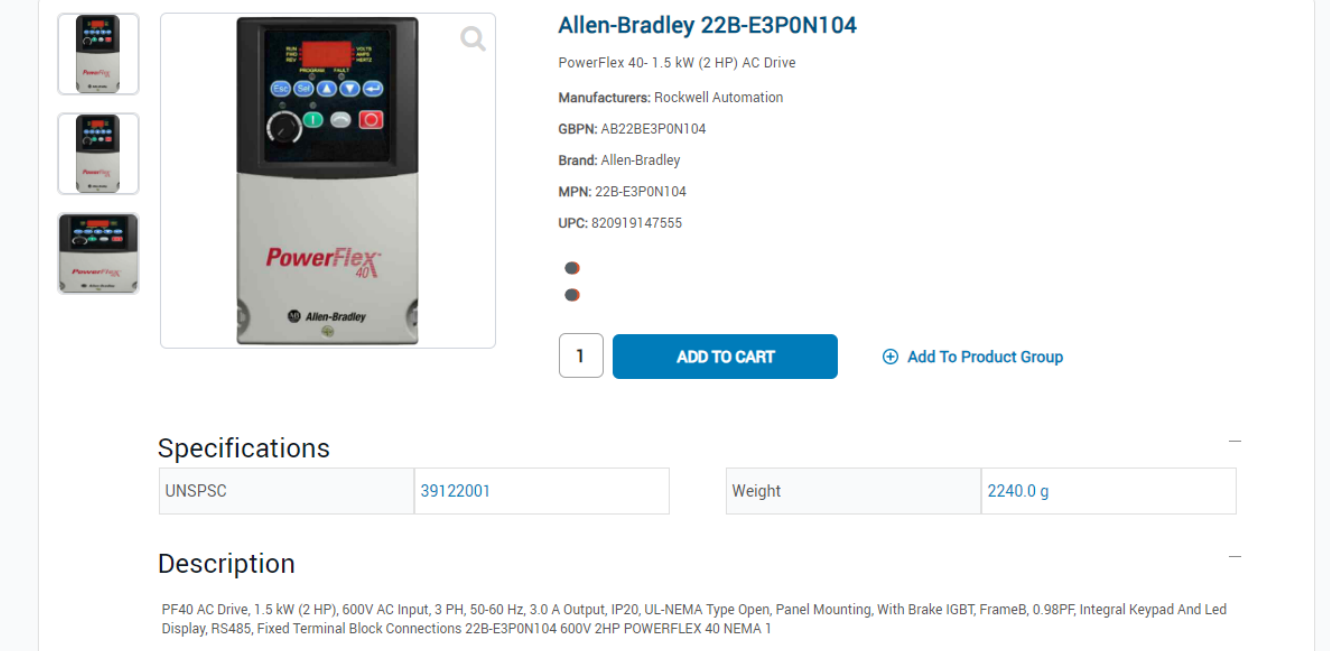


ABB Motors and Mechanical Inc.
Typical performance - not guaranteed values.
WINDING # 34WG0883
0.75 HP 3 PH 60 HZ 1725 RPM 460 V 3420M
TORQUES(LB-FT): PO=10 PU=8.5 LR=8.8 LRA=10
TORQUE
RPM
WATTS
AMPS
EFF
PF
%EFF
%PF
TORQUE (LB-FT)
RPM
WATTS
AMPS
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1,800
1,790
1,780
1,770
1,760
1,750
1,740
1,730
1,720
1,710
1,700
1,690
1,680
1,670
1,660
1,650
1,640
1,630
1,620
1,610
1,600
2,000
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
25
50
75
100
125
150
PERCENT OF RATED OUTPUT (0.75 HP)

Cutsheet for the VFD Under Test



Allen-Bradley 22B-E3P0N104

PowerFlex 40- 1.5 kW (2 HP) AC Drive

Manufacturers: Rockwell Automation

GBPN: AB22BE3P0N104

Brand: Allen-Bradley

MPN: 22B-E3P0N104

UPC: 820919147555

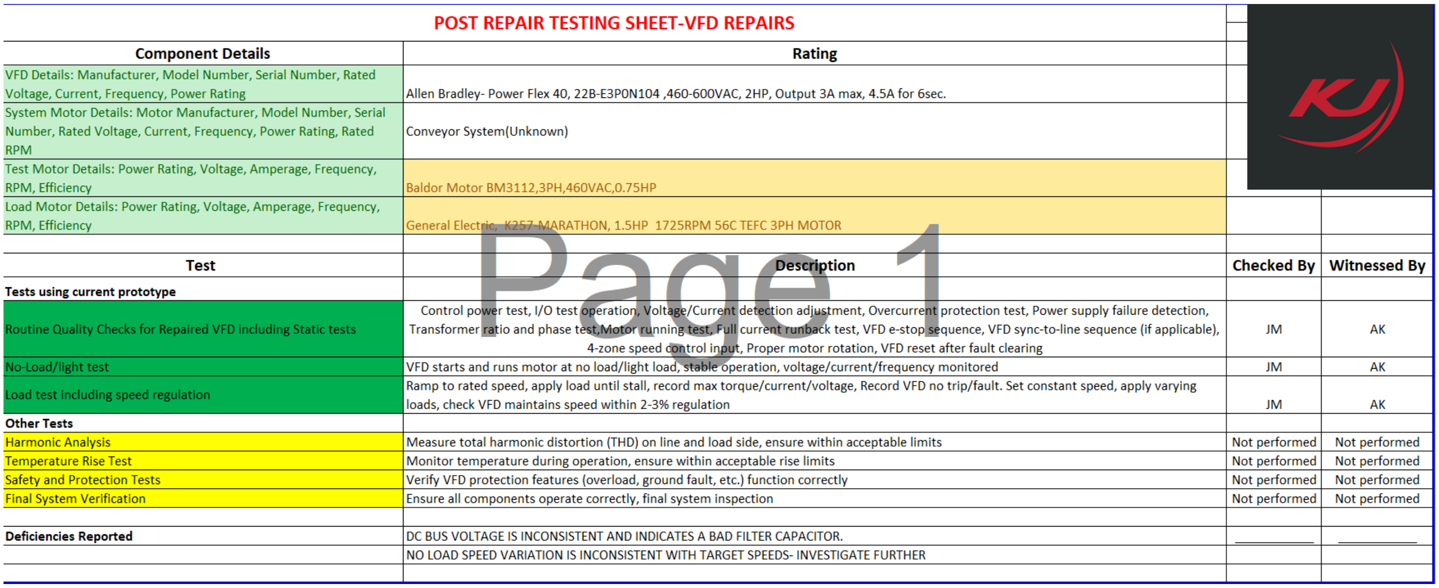
Specifications

UNSPSC	39122001	Weight	2240.0 g

Description

PF40 AC Drive, 1.5 kW (2 HP), 600V AC Input, 3 PH, 50-60 Hz, 3.0 A Output, IP20, UL-NEMA Type Open, Panel Mounting, With Brake IGBT, FrameB, 0.98PF, Integral Keypad And Led Display, RS485, Fixed Terminal Block Connections 22B-E3P0N104 600V 2HP POWERFLEX 40 NEMA 1

VFD checklist sheet



POST REPAIR TESTING SHEET-VFD REPAIRS

Component Details	Rating		
VFD Details: Manufacturer, Model Number, Serial Number, Rated Voltage, Current, Frequency, Power Rating	Allen Bradley- Power Flex 40, 22B-E3P0N104 ,460-600VAC, 2HP, Output 3A max, 4.5A for 6sec.		
System Motor Details: Motor Manufacturer, Model Number, Serial Number, Rated Voltage, Current, Frequency, Power Rating, Rated RPM	Conveyor System(Unknown)		
Test Motor Details: Power Rating, Voltage, Amperage, Frequency, RPM, Efficiency	Baldor Motor BM3112,3PH,460VAC,0.75HP		
Load Motor Details: Power Rating, Voltage, Amperage, Frequency, RPM, Efficiency	General Electric, K257-MARATHON, 1.5HP 1725RPM 56C TEFC 3PH MOTOR		
Test	**Description**	**Checked By**	**Witnessed By**
Tests using current prototype			
Routine Quality Checks for Repaired VFD including Static tests	Control power test, I/O test operation, Voltage/Current detection adjustment, Overcurrent protection test, Power supply failure detection, Transformer ratio and phase test,Motor running test, Full current runback test, VFD e-stop sequence, VFD sync-to-line sequence (if applicable), 4-zone speed control input, Proper motor rotation, VFD reset after fault clearing	JM	AK
No-Load/light test	VFD starts and runs motor at no load/light load, stable operation, voltage/current/frequency monitored	JM	AK
Load test including speed regulation	Ramp to rated speed, apply load until stall, record max torque/current/voltage, Record VFD no trip/fault. Set constant speed, apply varying loads, check VFD maintains speed within 2-3% regulation	JM	AK
Other Tests			
Harmonic Analysis	Measure total harmonic distortion (THD) on line and load side, ensure within acceptable limits	Not performed	Not performed
Temperature Rise Test	Monitor temperature during operation, ensure within acceptable rise limits	Not performed	Not performed
Safety and Protection Tests	Verify VFD protection features (overload, ground fault, etc.) function correctly	Not performed	Not performed
Final System Verification	Ensure all components operate correctly, final system inspection	Not performed	Not performed
Deficiencies Reported	DC BUS VOLTAGE IS INCONSISTENT AND INDICATES A BAD FILTER CAPACITOR.	___________	___________
	NO LOAD SPEED VARIATION IS INCONSISTENT WITH TARGET SPEEDS- INVESTIGATE FURTHER		