PLC-based Motor Speed Control

Part 3: Closed-Loop Controller Design

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EE 348L
Power Systems II Term Project

Contents

1 Introduction

For the term project of Powers Systems II, students designed a PLC-based motor speed controller for a three phase induction motor. The entire project consists of three distinct parts. In the first part, students determined all of the necessary components and started on the open-loop controller design. The second part involved system identification of the motor/load system. This team implemented system identification within the PLC controller for part 3. Part 3 achieved closed loop control of the system within specifications.

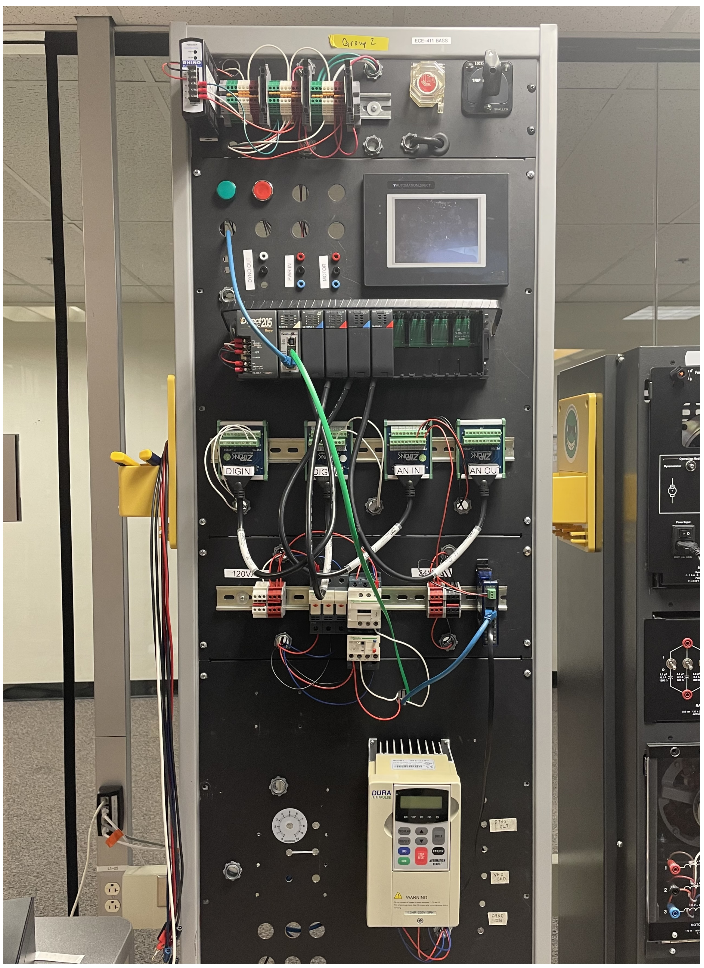


Figure 1: Full Rack Setup for Open-Loop Controller Design

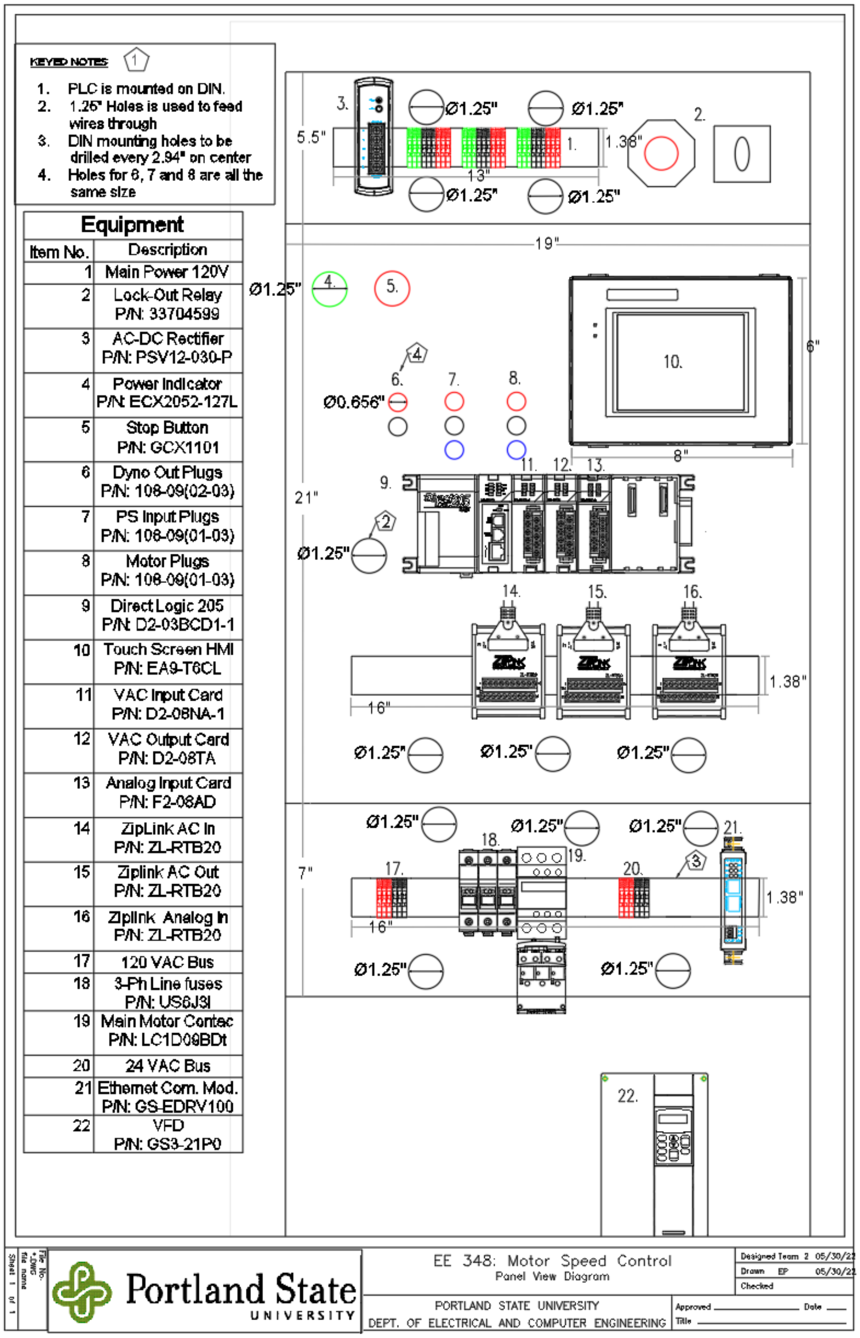
2 Bill of Materials

Bill of Materials						
	Item	*Vendor*	*Part Number*	*Quantity*	*List Price*	*Net Price*
1	Lock-out tag-out kit(4 pack)	Tradesafe	S42	1	$99.95	$99.95
2	Do-More CPU	Automationdirect	H2-DM1E	1	$445.00	$445.00
3	Direct Logic 205 PLC	Automationdirect	D2-03BCD1-1	1	$172.00	$172.00
4	22mm green light	Automationdirect	ECX2052-127L	1	$6.75	$6.75
5	22mm momentary red button	Automationdirect	GCX1101	1	$15.50	$15.50
6	Communication Cable	Automationdirect	EA-2CBL	1	$23.00	$23.00
7	C-more EA9 series touch screen HMI	Automationdirect	EA9-T6CL	1	$788.00	$788.00
8	RHINO PSB series switching power supply	Automationdirect	PSB12-030-P	1	$25.00	$25.00
9	5" Caster Kit(wheels)	Global Industrial	T9FRP1006	1	$34.95	$34.95
10	DIN Rail	Mouser	1207650	3	$6.92	$20.76
11	Rack 77"x19"	A-I Consolidated	RR-1369-MG	1	$388.93	$388.93
12	Fuse Holder	Schneider	DF103V	1	$16.58	$16.58
13	Non-reversing Contacter	Schneider	LC1D09BD	1	$69.92	$69.92
14	Fuse Holder	All Fuses	US6J3I	1	$65.24	$65.24
15	Lockout Relay	Radwell	33704599	1	$666.00	$666.00
16	3U Filler Panel	Rack Solutions	10-1825	2	$44.99	$89.98
17	12U Filler Panel	Allied	PBPA19010BK2	2	$47.23	$94.46
18	Ziplink Automation Direct	Automationdirect	ZL-RTB20	3	$27.00	$81.00
19	Ziplink PLC Cable	Automationdirect	ZL-BX-CBL40-1S	3	$33.00	$99.00
20	Bi-Metallic Overload Relay	Schneider	LRD06	1	$62.09	$62.09
21	PLC I/O Cable	Automationdirect	ZL-D2-CBL10	4	$29.00	$116.00
22	Variable Frequency Drive	Automationdirect	GS3-21P0	1	$271.00	$271.00
23	Ethernet Communication Module	Automationdirect	GS-EDRV100	1	$251.00	$251.00
24	Four-Pole Induction Motor	LabVolt	8221-00	1	$1,133.00	$1,133.00
25	Dynamometer	LabVolt	8960-20	1	$4,475.00	$4,475.00
26	Discrete Input Module	Automationdirect	D2-08NA-1	1	$57.59	$57.59
27	Discrete Output Module	Automationdirect	D2-08TA	1	$109.00	$109.00
28	Analog Input Module	Automationdirect	F2-08AD	2	$376.00	$752.00
29	Stranded Hook-up Wire, 18AWG, Red	Allied	18UL1007STRRED	10	$0.25	$2.50
30	Stranded Hook-up Wire, 18AWG, Green	Allied	18UL1007STRGRE	10	$0.25	$2.50
31	Stranded Hook-up Wire, 18AWG, White	Allied	18UL1007STRWHI	10	$0.25	$2.50
32	Stranded Hook-up Wire, 18AWG, Black	Allied	18UL1007STRBLA	10	$0.25	$2.50
33	Stranded Hook-up Wire, 18AWG, Blue	Allied	18UL1007STRBLU	10	$0.25	$2.50
34	Red Terminal Blocks(L)	Allied	70170163	3	$1.87	$5.61
35	Green Terminal Blocks(L)	Allied	70174131	3	$1.77	$5.31
36	White Terminal Blocks(L)	Allied	70175198	3	$1.87	$5.61
37	Banana Plug Patch Cord 48in Red	Allied	B-48-2	2	$7.19	$14.38
38	Banana Plug Patch Cord 48in Blue	Allied	B-48-6	2	$7.19	$14.38

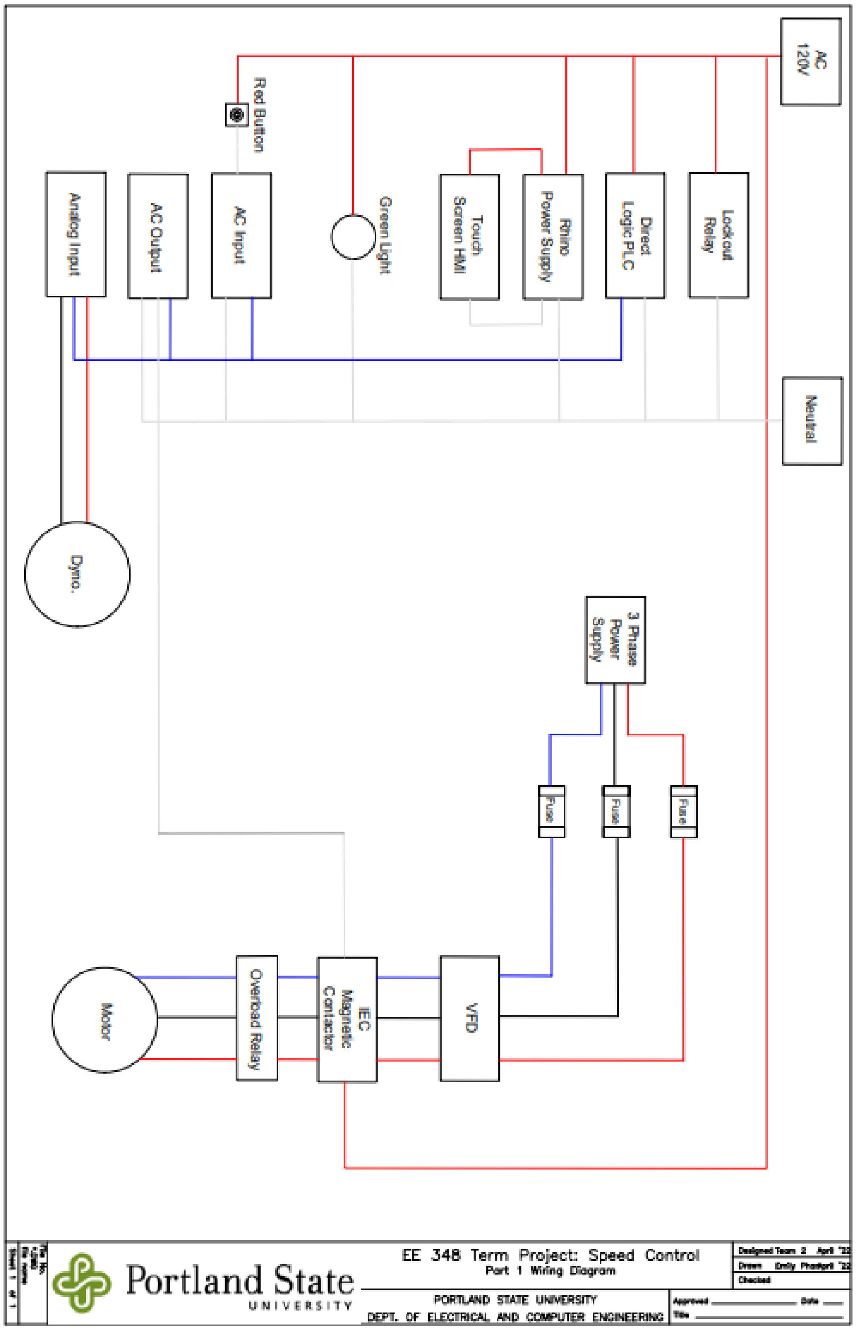
36	Banana Plug Patch Cord 48in Black	Allied	B-48-0	3	$7.19	$21.57
37	Banana Plug Patch Cord 48in White	Allied	B-48-9	4	$7.19	$28.76
38	Banana Test Connector Red	Newark	108-0902-001	2	$1.08	$2.16
39	Banana Test Connector Blue	Newark	108-0910-001	2	$1.08	$2.16
40	Banana Test Connector Blue	Newark	108-0901-001	1	$1.08	$1.08
41	Banana Test Connector Black	Newark	108-0903-001	3	$1.08	$3.24
42	Female Crimp Connector	Digi-Key	2-520184-2	22	$0.10	$2.20
43	Red Terminal Blocks(S)	Allied	3045127	3	$1.14	$3.42
44	Black Terminal Blocks(S)	Allied	3045088	3	$1.44	$4.32
45	White Terminal Blocks(S)	Allied	3045130	3	$1.44	$4.32
46	End Bracket	PSU EPL	NDN-EB35	3	$0.30	$0.90
46	End Cover	PSU EPL	DN-EC1210	6	$0.50	$3.00
47	Fuse	Super Breaker	FNM-8	3	$5.68	$17.04
Total						**$10,580.66**

Figure 2: Bill of Materials

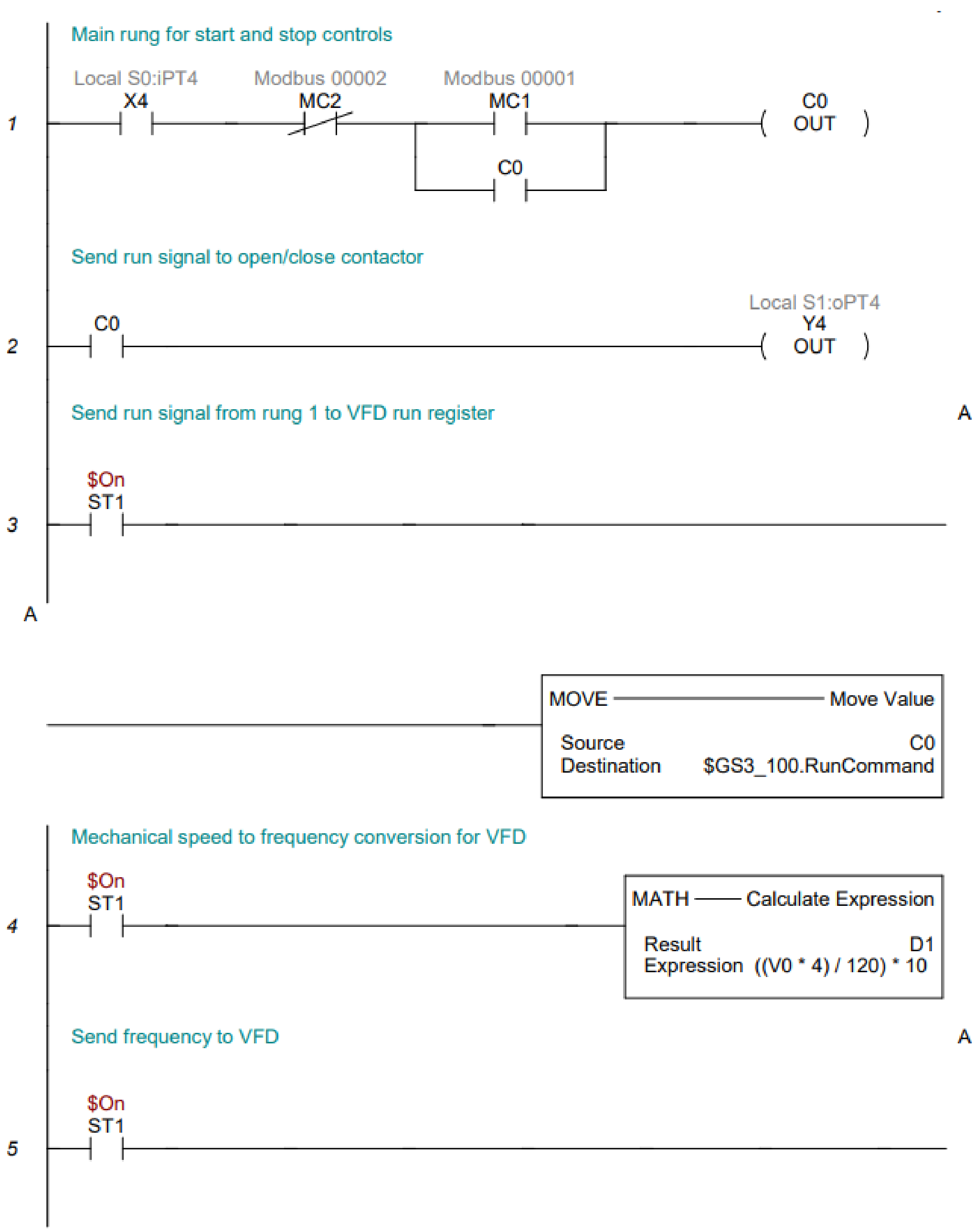
3 Panel Diagram

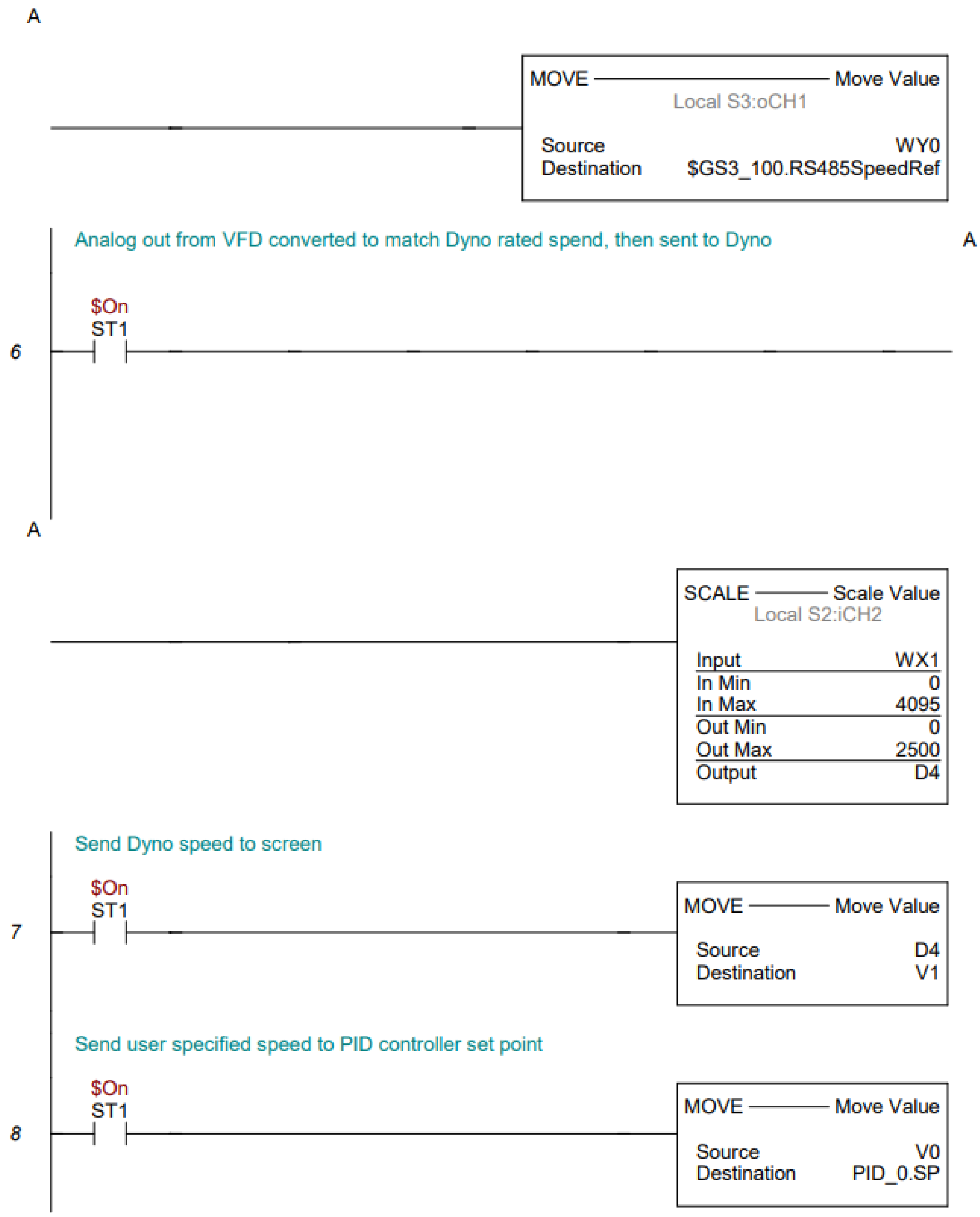


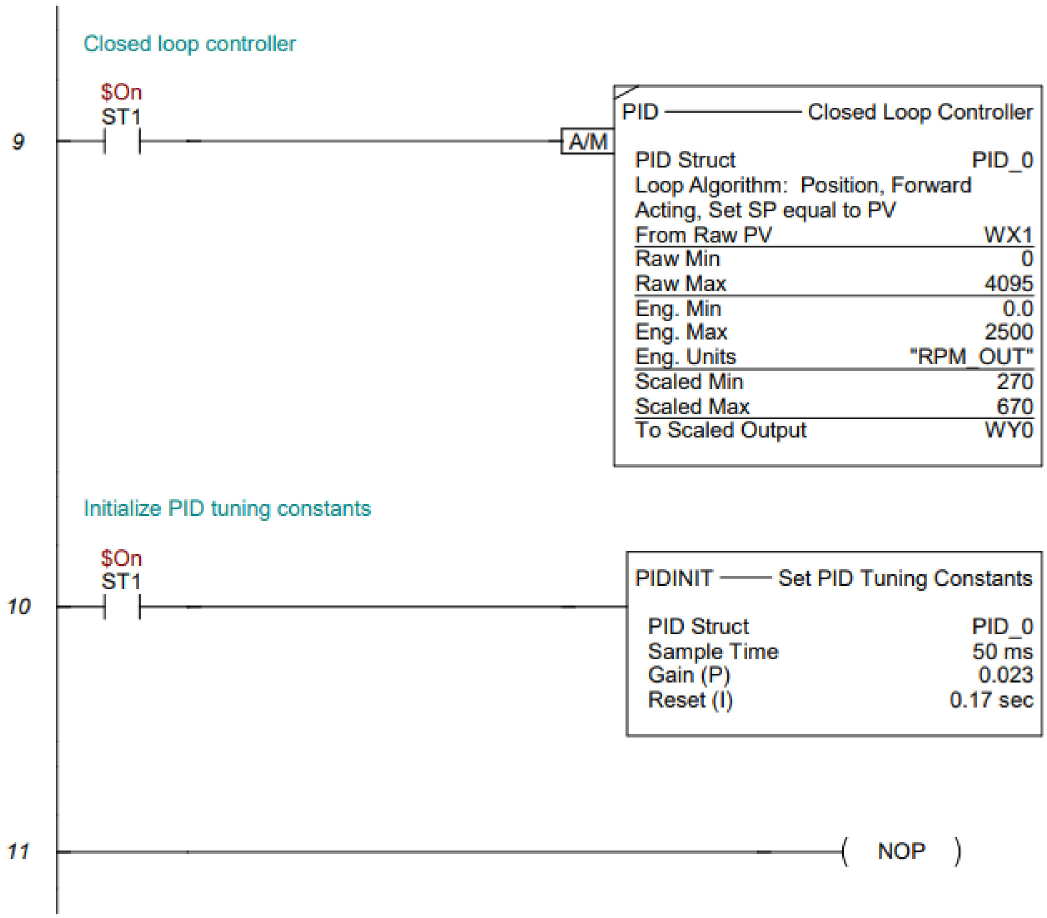
4 Wiring Diagram



5 PLC Ladder Logic Circuit Diagram




A
MOVE
Move Value
Local S3:oCH1
Source
WY0
Destination
$GS3_100.RS485SpeedRef
Analog out from VFD converted to match Dyno rated spend, then sent to Dyno
A
$On
ST1
6
A
SCALE
Scale Value
Local S2:iCH2
Input
WX1
In Min
0
In Max
4095
Out Min
0
Out Max
2500
Output
D4
Send Dyno speed to screen
$On
ST1
7
MOVE
Move Value
Source
D4
Destination
V1
Send user specified speed to PID controller set point
$On
ST1
8
MOVE
Move Value
Source
V0
Destination
PID_0.SP


Closed loop controller
$On
ST1
9
A/M
PID —— Closed Loop Controller
PID Struct PID_0
Loop Algorithm: Position, Forward Acting, Set SP equal to PV
From Raw PV WX1
Raw Min 0
Raw Max 4095
Eng. Min 0.0
Eng. Max 2500
Eng. Units "RPM_OUT"
Scaled Min 270
Scaled Max 670
To Scaled Output WY0
Initialize PID tuning constants
$On
ST1
10
PIDINIT —— Set PID Tuning Constants
PID Struct PID_0
Sample Time 50 ms
Gain (P) 0.023
Reset (I) 0.17 sec
11
NOP

6 Point Lists

POINT ASSIGNMENT INDEX

REV	DATE	DESCRIPTION	CREATED BY	CHECKED BY
1	04/15/2022	Created Pointlist	NT	EP
2	04/15/2022	Edited points list of 4-pole squirrel cage induction motor	NT	EP
3	04/15/2022	Edited thermal overload relay	NT	EP
4	04/15/2022	Edited LabVolt Power Supply	NT	EP
5	04/15/2022	Edited Contactor	NT	EP
6	04/15/2022	Edited fuse holder	NT	EP
7	04/15/2022	Edited VFD	NT	EP
8	05/13/2033	Edited Direct Logic 205	NT	EP
9	05/13/2033	Edited AC/DC Rectifier	NT	EP
10	05/13/2033	Edited Touch Screen	NT	EP

Table 1. Check List

4-pole squirrel cage induction motor, 8821		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
Phase A Terminal Left	1	0	0	0	0	1	0	T1	Thermal overload relay, T1 terminal
Phase B Terminal Left	2	0	0	0	0	1	0	T2	Thermal overload relay, T2 terminal
Phase C Terminal Left	3	0	0	0	0	1	0	T3	Thermal overload relay, T3 terminal
Phase A Terminal Right	4	0	0	0	0	1	0	N	Power Supply, N Terminal
Phase B Terminal Right	5	0	0	0	0	1	0	N	Power Supply, N Terminal
Phase C Terminal Right	6	0	0	0	0	1	0	N	Power Supply, N Terminal
	Total Points	0	0	0	0	6	0		

Table 2. 4-Pole Squirrel Cage Induction Motor Points List

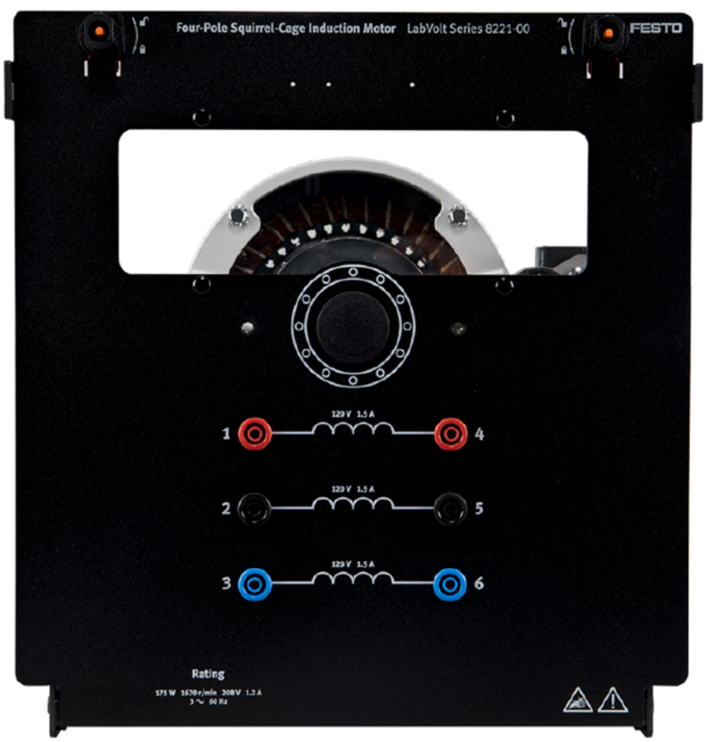


Figure 1. 4-Pole Squirrel Cage Induction Motor

Thermal Overload Relay		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
T1 Terminal	T1	0	0	0	0	1	0	1	Squirrel Cage Inducton Motor, Phase A Terminal Left
T2 Terminal	T2	0	0	0	0	1	0	2	Squirrel Cage Inducton Motor, Phase B Terminal Left
T3 Terminal	T3	0	0	0	0	1	0	3	Squirrel Cage Inducton Motor, Phase C Terminal Left
97 NO Terminal	97 NO	0	0	0	0	1	0	120 AC-Line	120 AC-Line
98 NO Terminal	98 NO	0	0	0	0	1	0	CH4	Digital Output Ziplink
	Total Points	0	0	0	0	5	0		

Table 3. Thermal Overload Relay Points List

Figure 2. Thermal Overload Relay

3 Phase Power Supply		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
AC fixed 120/208V Phase A	1	0	0	0	0	1	0	L1	Contactor, L1 Terminal
AC fixed 120/208V Phase B	2	0	0	0	0	1	0	L2	Contactor, L2 Terminal
AC fixed 120/208V Phase C	3	0	0	0	0	1	0	L3	Contactor, L3 Terminal
AC fixed 120/208V Neutral	N	0	0	0	0	1	0	4	Squirrel Cage Inducton Motor, Phase A Terminal Right
AC fixed 120/208V Neutral	N	0	0	0	0	1	0	5	Squirrel Cage Inducton Motor, Phase B Terminal Right
AC fixed 120/208V Neutral	N	0	0	0	0	1	0	6	Squirrel Cage Inducton Motor, Phase C Terminal Right
	Total Points	0	0	0	0	6	0		

Table 4. LabVolt Power Supply, 8821 Points List

Figure 3.LabVolt Power Supply, 8821

Contactor		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
L1 Terminal	L1	0	0	0	0	1	0	L1	VFD, L1 Terminal
L2 Terminal	L2	0	0	0	0	1	0	L2	VFD, L2 Terminal
L3 Terminal	L3	0	0	0	0	1	0	L3	VFD, L3 Terminal
A1 Terminal	A1	0	0	0	0	1	0	120 AC-Line	120 AC-Line
A2 Terminal	A2	0	0	0	0	1	0	CH0	Digital Input Ziplink
	Total Points	0	0	0	0	5	0		

Table 5.Contactor Points List

Figure 4. Contactor

Fuse Holder, DF 103		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
Top Terminal	1	0	0	0	0	1	0	1	3 Phase Power Supply, AC fixed 120/208V Phase A
Top Terminal	2	0	0	0	0	1	0	2	3 Phase Power Supply, AC fixed 120/208V Phase B
Top Terminal	3	0	0	0	0	1	0	3	3 Phase Power Supply, AC fixed 120/208V Phase C
Bottom Terminal	4	0	0	0	0	1	0	L1	VFD, L1 Terminal
Bottom Terminal	5	0	0	0	0	1	0	L2	VFD, L2 Terminal
Bottom Terminal	6	0	0	0	0	1	0	L3	VFD, L3 Terminal
	Total Points	0	0	0	0	6	0		

Table 6.Contactor Points List

Figure 5. Fuse Holder

VFD		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
L1 Terminal	L1	0	0	0	0	1	0	4	Fuse Holder, Bottom Terminal
L2 Terminal	L2	0	0	0	0	1	0	5	Fuse Holder, Bottom Terminal
L3 Terminal	L3	0	0	0	0	1	0	6	Fuse Holder, Bottom Terminal
T1 Terminal	T1	0	0	0	0	1	0	L1	Contactor, L1 Terminal
T2 Terminal	T2	0	0	0	0	1	0	L2	Contactor, L2 Terminal
T3 Terminal	T3	0	0	0	0	1	0	L3	Contactor, L3 Terminal
	Total Points	0	0	0	0	6	0		

Table 7.VFD Points List

Figure 6. VFD

Direct Logic DL 205 1-0 Base, D2-09B-1		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
Top Terminal	100-240V	0	0	0	0	1	0	120 AC-Line	120 AC-Line
Second Terminal	100-240V	0	0	0	0	1	0	120 AC-Line	120 AC-Line
G Terminal	G	0	0	0	0	1	0	120 AC-Line	120 AC-Line
Second Bottom Terminal	24V	0	0	0	0	1	0	24 DC	24 DC
Bottom Termial	24V	0	0	0	0	1	0	24 DC	24 DC
	Total Points	0	0	0	0	5	0		

Table 7. Direct Logic 205 Points List

Figure 8. Direct Logic 205

PSB12-030-P		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
Positive Terminal	(+)	0	0	0	0	1	0	(+)	Touch Screen, Positive Terminal
Negative Terminal	(-)	0	0	0	0	1	0	(-)	Touch Screen, Negative Terminal
Grounding Terminal	⏚	0	0	0	0	1	0	120 AC-Line	120 AC-Line
N Terminal	N	0	0	0	0	1	0	120 AC-Neutral	120 AC-Neutral
L Terminal	L	0	0	0	0	1	0	120 AC-Line	120 AC-Line
	Total Points	0	0	0	0	4	0		

Table 8. AC/DC Rectifier Point Lists

Figure 9. AC/DC Rectifier

Touch Screen HMI		POINT TYPE							
		Hardware Point							
Point Description	Origin Address	DO	DI	AO	AI	Pwr	Virtual Point	Destination Address	Destination Description
Positive Terminal	(+)	0	0	0	0	1	0	(+)	PSB12-030-P, Positive Terminal
Negative Terminal	(-)	0	0	0	0	1	0	-	PSB12-030-P, Negative Terminal
	Total Points	0	0	0	0	2	0		

Table 9. Touch Screen Point Lists

Figure 10. Touch Screen

7 Operator's Manual

7.1 Instruction on how to operate the system

Notes

- Review and understand safety and lock-out/tag-out procedures
- Review necessary data sheets and NFPA 70 standards included in this report
- Green light indicates power applied to system
- Red button on panel and touch screen can be used to stop all operations
- Green button on touch screen is used to start operation
- ”Load RPM Dyno” displays RPM reading from dynamometer

System Setup: Connect the LabVolt Power Supply through the control rack to the motor in Wye configuration with a floating neutral line.

- Couple the dynamometer to the Squirrel cage motor
- Connect three phase power from the direct AC power supply to the PWR IN terminals on the rack.
- Connect three phase power from the MOTOR terminal on the rack to the primary terminals of the squirrel cage motor in Wye configuration.
- Connect the two DC terminals marked DYNO OUT to the ANALOG OUTPUT terminals of the dynamometer, the white cable connects to the yellow speed output terminal (labeled with a small n) and the black cable connects to the white ground terminal.
- Plug in the 120VAC power cord from the rack and press the red lock-out button to supply the rack control systems with 120VAC
- Supply three phase power to the rack by flipping switch on Power Supply

- Set the PLC to "run" mode by flipping the small switch located on the PLC CPU module.

Operation

1. Ensure the power supply is both plugged in and turned on
2. Set the load torque on the Dynamometer by adjusting the manual control knob and initializing manual control with the START/STOP button.
3. Press "RPM Set" on the touch screen located on the rack and set desired RPM within range: [800 2000] rpm
4. Press the green button on the touch screen to start the motor.
5. Observe the measured speed of the load dynamometer in RPMs on the screen and compare to the set speed
6. Set the "RPM Set" on the screen while the motor is running and press enter to observe the step response of the motor
7. Press red button on either panel or screen to stop the motor

Figure 3: C-More Touch Screen

Shut Down

1. Turn off the 3 Phase Power Supply by flipping the switch down. Observe proper lockout/tagout procedures.
2. Turn off power to the rack by turning the lockout relay at the top/right of the rack to the "12-to-6" position.
3. Then proceed to unplug all connections.

7.2 Commented checklist of realized specifications

Part 1:

1. A DL205 PLC **shall** be used to provide open loop control of a motor.
    - The DL205 is used in the design of the system and is what controls the system.
2. Power **shall** be provided to the control circuits via appropriate PLC outputs.
    - This was done by connecting the light and buttons to the ZIPLink feed through module that is controlled and powered by the PLC.
3. The PLC shall be powered by a 120 VAC source.
    - This was done by connecting the hot 120 VAC wire to positive PLC terminal, the neutral 120 VAC wire to the negative PLC terminal, and the ground wire to the ground terminal.
4. Power to the PLC shall be protected by a lock-out/tag-out mechanism.
    - Lock-out/tag-out procedures were followed. When someone was working on the system padlocks were attached to the lock-out/tag-out panel.
5. The PLC shall be protected on the 120 VAC side by an appropriately-rated fuse.
    - A 2A rated fuse was attached to the 120VAC hot wire to protect the PLC.
6. The motor to be controlled shall be a LabVolt 8221 four pole squirrel cage induction motor.
    - This was accomplished by connecting the system to a LabVolt 8221 four pole squirrel cage induction motor in the power lab.
7. The motor shall be protected against overcurrent conditions.
    - This was done by connecting an overload relay to the contactor.

8. The controller shall provide open-loop speed control over range [800 2000] rpm.
    - The controller is implemented in C-More software with the specific range set. No values outside of range can be used.
9. Real-time motor RPM data shall be made available to the user.
    - RPM reading is taken from Dynamometer. A display window is available on touch screen and displays same reading as shown on Dynamometer.
10. A red button shall be available to stop the system
    - The connections of the red button were achieved by connecting to 120 AC-Line and AC Input Module.
11. A green light should be used to indicate that power is available.
    - The green light connects to 120AC-Line and other side connects to 120AC-Neutral
12. All operator inputs should be available via a touch screen.
    - Start and stop button and speed input controls is located on screen.
13. All operator outputs should be available via a touch screen.
    - RPM reading is displayed on touch screen.
14. All components shall be mounted on 19" rack panels.
    - All components used for project is mounted on rack panels.
15. Appropriate and consistent color coding should be used for all conductors and terminal blocks.
    - All conductors and terminals are color coded so that hot is red, neutral is white, and ground is green.

Part 3:

1. Overshoot shall be less than 10%
   - No overshoot in the step response.
2. Settling time shall be less than or equal to 3.0 seconds
   - 2.4 second settling time.
3. Rise time shall be less than or equal to 1.0 second
   - 0.5 second rise time
4. Peak time shall be less than or equal to 1.5 second
   - 0.9 second peak time

7.3 Validation of closed-loop time-domain response specifications

The step response of this design are shown in figure 4 below. The specifications ask for overshoot to be less than 10%. Our design has no overshoot in its step response. The settling time is 2.4 seconds, under the 3.0 seconds requested. The rise time, taken from 10% to 90% of the step response, is 0.5 seconds. The peak time is more unclear, since there is no overshoot, but we measured it as 0.9 seconds. All these values are within specification.

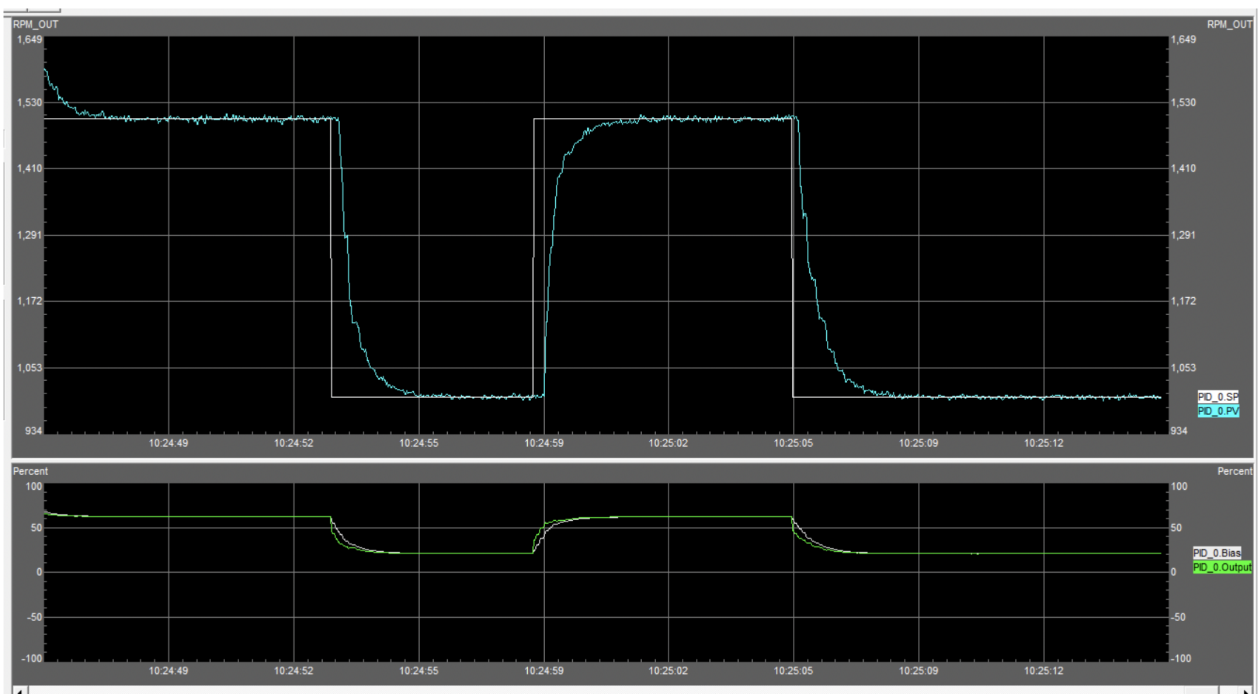


Figure 4: Sample run stepping between 1500 and 1000

7.4 Discussion of the PI compensator design process

Once we set up the PID block, we set the output to control the set point variable and ran an auto-tune test. Auto-tune cycles the set point from 0% to 100% and returns P and I coefficients and a sample time. We used these to initialize the PI controller and then observed the effects.

At this point we started adjust the PI values to reduce the spike observed upon motor startup. However, this was not required per the project specifications, instead requiring us to smooth the step up and down response.

With our newfound understanding of the project specifications, we found that our previous tinkering of the PI values had actually achieved a step response within spec. Essentially we spent a very long time trying to fix something that was not required of us and while doing so had inadvertently achieved the final specifications.

The final coefficients we used were $K_P = 0.023$, $K_I = 0.170$, with a sampling time of 50 ms.

7.5 Notes on the use of relevant NFPA 70 standards

- 200.6(A) Grounding Wire Identification - Neutral lines are identified by wire with a white sheath.
- 210.20(A) 1.25 Ampacity factor needed for overcurrent protection - Max current in system is present in the PLC, which is rated for 80VA supplied by 120V. This results in a max current of less than 1A, 2A fuses available through the EPL satisfy overcurrent protection.
- 240.4(D)(1) Protection of Conductors - As previously calculated, max current will not exceed 1A. 18 AWG wire was the only gauge available from the EPL and still satisfies the rating.
- 240.6 Standard Ampere Ratings - 2A Fuses available through EPL are non-standard but still satisfy safety ratings
- 200.6 Identifying Grounded Conductors - Ground lines are identified by wire with green sheath.
- 120.4 Simple Lockout/Tagout - Lockout procedures followed during all operation and troubleshooting via a plastic cover over the main power button.
- 310.10(A) Conductor use in dry locations - Lab humidity is regulated by building HVAC
- 420.6(2) Nameplate Values - Labvolt motor is rated for 1.2A and is protected by a thermal overload relay set for 1.5A.
- 430.36 Fuses - In Which Conductor - Three phase overcurrent protection provided with a 8A fuse for each phase.
- 430.38 Number of Conductors Opened by Overload Device - Thermal overload relay programmed to disconnect all three phases simultaneously, preventing a surge in a single phase.

- 430.82(A) Controller Design - Physical stop button placed on rack as well as a programmed stop function on touch screen will de-energize circuit.
- 430.102(A) Location - Controller - All interfaces for plant are within arms reach of motor. Rack is located adjacent to Labvolt equipment.