Automated testing framework for Medium voltage drive using Hardware in Loop System & Emulator Setup

Major Project Report

(Part-II)

Submitted in partial fulfillment of the requirements for

Semester-IV of

Master of Technology

In

Electrical Engineering

(Power Electronics, Machines & Drives)

Submitted By

Bamania Mihir Piyushbhai

(17MEEP09)

Department of Electrical Engineering

Institute of Technology

NIRMA University

Ahmedabad - 382481

May 2019

Certificate

This is to certify that the Project Report entitled **"Automated testing framework for Medium voltage drive using Hardware in Loop System & Emulator Setup"** submitted by **Bamania Mihir (Roll No: 17MEEP09)**, towards the partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical Engineering (Power Electronics,Machines and Drives) of Nirma University, Ahmedabad, is the record of work carried out by her under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this project work, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

Date :

Mr. Nitin Adlok
Industry Guide
Team-RMDR MVD
ABB-GISPL
Bhoruka Tech Park
Bangalore

Dr. Siddharthsingh K. Chauhan
Institute Guide
Associate Professor
Department of Electrical Engineering
Institute of Technology
Nirma University

Prof. Dr. S. C. Vora
Head of Department
Department of Electrical Engineering
Institute of Technology
Nirma University

Additional Director
School of Engineering
Institute of Technology
Nirma University

Statement of Originality

I, **MIHIR BAMANIA**, En. No. **17MEEP09**, give undertaking that the Major Project entitled "**Automated testing framework for Medium voltage drive using Hardware in Loop System & Emulator Setup**" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electrical Engineering (Power Electronics, Machine & Drives)** of Institute of Technology, Nirma University, Ahmedabad, contains no material that has been awarded for any degree or diploma in any university or school in any territory to the best of my knowledge. It is the original work carried out by me and I give assurance that no attempt of plagiarism has been made.It contains no material that is previously published or written, except where reference has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

Mihir Bamania

____

Date:

Place:

Endorsed by

Mr. Nitin Adlok

____

Acknowledgements

I am very thankful to Mr. Nitin Adlok-Test Lead, RMDR MVD Team, ABB GISPL Bangalore for his constant support & valuable guidance as a mentor throughout project duration. I would also like to thank Mr. Shriram S-Product Owner, RMDR MVD Team, ABB GISPL Bangalore for supporting project work & improvement in it.

I am grateful to Mr. Kuruvilla Taji-Line Manager, RMDR Team, ABB Bangalore for supporting my project work & I would also like to thank all RMDR MVD team for providing effective guidance for this project and encouraging me to pursue it.

I would like to express deepest appreciation towards Dr. Siddharthsingh K. Chauhan, Associate Professor, Department of Electrical Engineering, Institute of Technology, Nirma University for supporting project & valuable inputs as institute guide. I am really thankful to Dr. S.C. Vora, HOD, Electrical Engineering, Institute of Technology, Nirma University for allowing me to pursue my internship at ABB GISPL, Bangalore.

At last I must express my sincere heartfelt gratitude to all the employees of ABB GISPL, Bangalore who helped me directly or indirectly during project work & internship.

Mihir Bamania
17MEEP09

Abstract

In global market, ABB is a main worldwide provider of medium voltage drives in the range of 250 kW to more than 100 MW. ABB supplies medium voltage adjustable speed drives for an extensive variety of uses like in the mining and minerals, water, metals, cement, marine, control and compound, oil and gas businesses. Electric drives are utilized to adjust speed of motor to the required speed, subsequently increase in energy efficiency & dynamic response.

In Automated testing framework [ATF], testing of drive is carried out automatically to reduce human efforts, to improve efficiency & for safety reasons. Before releasing drive to end user, it is extremely necessary to perform application software testing. Here Manual testing & Automated testing are performed using Hardware in Loop system as well as Emulator setup on drive. Various testcases explain requirements & benefits of ATF over Manual testing.

The Aim of the project is to perform testing using **"Automated testing framework"** for medium voltage drive, **"Hardware in Loop System & Emulator Setup**". In this project various testing has been carried out which are performed on medium voltage drive according to applications.

Abbreviations

AI	Analog Input
AO	Analog Output
ATF	Automated testing framework
C#	C Sharp
CVMi	Current & Voltage Measuring instruments
DI	Digital Input
DO	Digital Output
DSW	Drive Status Word
EMU	Emulator
HiL	Hardware in Loop
MCB	Miniature Circuit Breaker
MVD	Medium Voltage Drive
MS	Microsoft
OL	Over Load
RPM	Revolutions per Minute
RT	Real Time
ULC	User Load Curve
UL	Under Load
VSD	variable Speed Drive

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Medium Voltage Drives

Drives are utilized for controlling torque, speed or power on motor shaft by changing constant voltage and frequency of input applied to drive . Around 65% of the world's industrial power is utilized by electric drives or motors and industry represent 33% of the world's power utilization which is major part in terms of electricity usage.[14]

Medium-voltage (MV) AC drives deliver many occasions more prominent power yield than various low-voltage (LV) drives. Medium Voltage Drives are utilized to run electric motors loaded for example by fans, blowers, factories, crushers, blenders and so forth.[15]

MVD gives process control, so it can expand efficiency of plant production, decrease various type of energy losses, enhance hardware protection in terms of safety, decrease equipment's maintenance cost with increased reliability.

These drives are utilized in such a manner that they can adapt motor speed to the actual required speed for application, hence providing better energy consumption. The modified drive arrangements convey quick and precise control of dynamic procedures, for example, those found in the metals, marine and mining enterprises. below figure indicates functional diagram of MVD system with various functional blocks.[12]

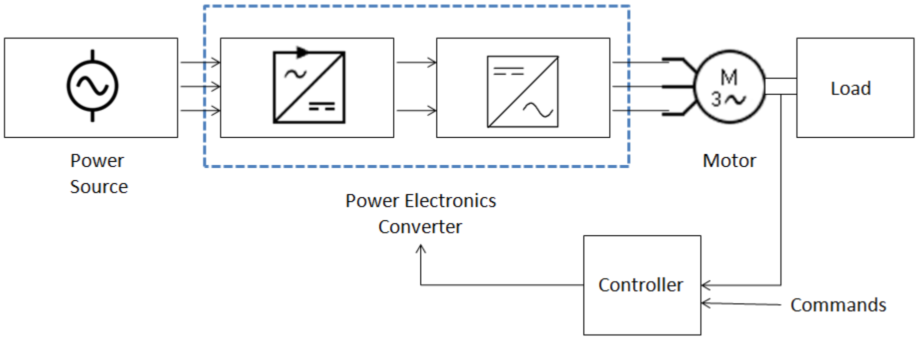

Figure 1.1: Basic block of Electrical Drive System

ABB owns various medium voltage drives with different ratings & specifications for applications.

ABB contains following MV drives:[16]

Table 1.1: ABB Medium Voltage Drives with ratings

No	Name	Power rating	Voltage rating
1	ACS1000	315 KW - 5 MW	2.3 - 4.16 KV
2	ACS2000	250 KW - 3680 KW	4 - 6.9 KV
3	ACS5000	2 MW - 36 MW	6 - 13.8 KV
4	ACS6000	3 MW - 36 MW	upto 3.3 KV
5	MEGADRIVE-LCI	2 MW - 150 MW	2.1 - 25 KV
6	ACS580 MV	200 KW - 6300 KW	6 - 11 KV

1.2 Applications of MVD

As ABB has extensive variety of medium voltage drives, ABB makes medium voltage variable speed drives for an extensive variety of utilization in different types of industries. Few of applications are described ahead like Cement Industries, Mining and Minerals; for Power sectors applications; water; metals industries; marine sectors & chemical plants, oil and gas ventures & so more.

1. **Drives and motors for the cement industries :**

By using Variable speed drives (VSD) to control high efficiency motors in cement manufacturing process, It is possible to reduce energy consumption significantly compared to traditional fixed speed motors. VSDs also provide an accurate control for various processes.

2. **Drives and PLCs for oil and gas industries :**

There are many applications in oil and gas industry that use electrical motors. ABB MV drives and PLCs can help to operate motors more efficiently and reliably.

3. **Drives and motors for pulp and paper industries :**

Variable frequency drives (VFD) are designed to provide reliable control over the speed and torque of motors so that they can run according to the precise demands of process. From pulp processing to paper, board and tissue machines, utilizing ABB medium and low voltage drives implies more effective energy utilization at most of operating hours & reduces operating expenses.

4. **Drives and PLCs for metals :**

Metals processing needs reliability at first priority. The hardware needs to move the metals rapidly, precisely and effectively. The procedures require a lot of energy, high dynamics as well as accuracy and over-load abilities. To guarantee optimum efficiency of the system most of time, safety and easy maintenance of the gear are fundamental.

In high temperature or cold rolling mills, blast furnace blowers, sinter fans or general pumps and fans, ABB provides a variable speed drive for it. ABB products offer accurate speed and torque control starting from low voltage drives to megawatt range of medium voltage drives. Due to precise process control, drives help you to save energy and improve production quality. PLCs provide scalable flexibility for the whole process.[17]

These drives consist of below features :

- Direct torque control (DTC) makes drives faster and have precise speed and torque control
- Drives are able to catch and reuse motor braking energy in braking operations

1.3 Essential features of Medium Voltage Drive:

Medium voltage drive has numerous advantages & features. Essential features of medium voltage drive are mentioned as follow:

- Assistant control panel
- Optional slots are available & built-in energy calculators
- Connection to all major industrial automation systems via plug-in Fieldbus and Ethernet adapters
- USB interface for PC tool connection : USB port for transferring information between PC and drive

Chapter 2

Testing of Medium Voltage Drives

2.1 Types of Testing

ABB medium voltage drive has many applications in which high power & dynamic response are required. It is necessary to test control software before releasing it to market. In Software testing, various types of testing are carried out such as Manual Testing, Smoke testing, Functional Testing, Non Functional Testing, Automation Testing etc. These testings can be performed on software according to requirements.[10]

Various types of testing are listed as below:

- Functional Testing
- Smoke testing
- Integration testing
- System testing
- Black Box Testing
- Unit testing

1. Unit testing : Testing of an individual software segment or module is named as Unit Testing in Software testing. It is commonly done by the software engineers and not by analyzers, as it requires definite information of the interior program structure and code.

2. Integration testing : Testing of every coordinated module to check the joined usefulness after integration is named as Integration Testing. Modules are usually code modules, singular applications, client-server applications on a system, and so forth.

The goal is to take unit tested parts and construct a program structure that has been managed by design. Integration testing will be trying in which a gathering of segments are consolidated to deliver output.[4]

3. System testing : In System Testing method, the whole framework is tested according to requirements. It is one type of Black-box testing that is based on in general requirement specifications and covers all the joined parts of a framework. In this, software is tested with the end goal that it works fine for various working system. Framework testing is finished with full system usage and condition.

4. Functional Testing : This kind of testing overlooks the inside parts and concentrates just on the output to check in the event that it is according to the necessity or not. Functional testing is a software testing process utilized inside software improvement in which programming is tried to guarantee that it acclimates with all prerequisites. Practical testing guarantees that the necessities are appropriately fulfilled by the application.[9]

5. Black Box Testing : Black box testing is a software testing strategy that examines the usefulness of a software without knowing much about internal structure or plan of thing which is being tested. Black box testing is also known as closed box.

2.2 Technical configuration of Medium voltage Drive

Automated testing & Manual testing have been carried out on drive with below mentioned drive configurations.

Motor rated Voltage	Input 6 kV to 11 kV +- 10%
	Output 6 kV to 11 kV
Power range	200 to 3500 kW ; for 6 kV
Supply frequency	50/60 Hz +- 5%
Motor Frequency	0 to 120 HZ Output
Motor Control	Scalar Control
Power Factor	greater than 0.96
Drive system efficiency	96 % including X'mer + Aux. losses
PC tools	Drive composer tool entry
Maximum motor cable length	1000m
Overload	110% [1 min - 10 min]
Control connections	Analog inputs [AI] (4)
	analog outputs [AO] (2)
	digital inputs [DI] (6 + 6 predefined)
	digital outputs [DO] (5 + 4 predefined)
FieldBus Adapters	PROFIBUS DP, Ehternet/IP
	MODBUS TCP/RTU
Cooling method	Air Cooled [Dry Clean Air]
Safety feature	Emergency Stop, Safe torque off

2.3 Manual Testing of Medium Voltage Drive

As developer develops the application according to functionalities, where tester can generate testcase for an application which compares actual value & expected value. If there are bugs during test, then bugs are reported by tester to developer to resolve them.[5]

After Manual testing, tester defines test steps for specific tests to use it in Automated testing commands. Here Manual testing is carried out on testcases using Emulator System. Manual testing allows tester to check if functionality is correctly feasible or not. Manual testing performs as important part before Automated testing.[3]

Manual testing has few demerits. Testing of system in manual methods leads to :

- Reduced test efficiency
- Increased probability of risks
- More time requirement
- Human intervention
- Errors in results
- Safety issues

Hence, it is necessary to perform in Automated testing manner instead of Manual testing.

2.4 Automated Testing Framework of Medium Voltage Drive

Testing frameworks are very important segment of any successful automated testing process. These frameworks are agile to reduce testing efforts as well as maintenance costs for testing. With ATF, it is possible to create and run automated tests for the system which is present for testing purposes.

By using an ATF for any System testing, it will increase test speed and test efficiency. It can also improve test accuracy. In addition, it will reduce test maintenance costs as well as lower risks also. A common trend to minimize risk is to test earlier in the Automation testing framework rather than field fault occurrences in Systems.[2]

Automated Testing Frameworks are essential to an efficient Automated testing process due to below mentioned key factors :

- Improved test efficiency
- Lower maintenance costs
- Maximum test coverage
- Effective automatically generated reports
- Reusability of code
- Safety
- Ease of changing Configuration

As shown in below flowchart, it explains Automated testing framework. In Automated testing framework, testcase codes for various tests are written in C# language in Microsoft Visual studio. To establish drive communication, DDCS communication protocol helps to initialize it.[1]

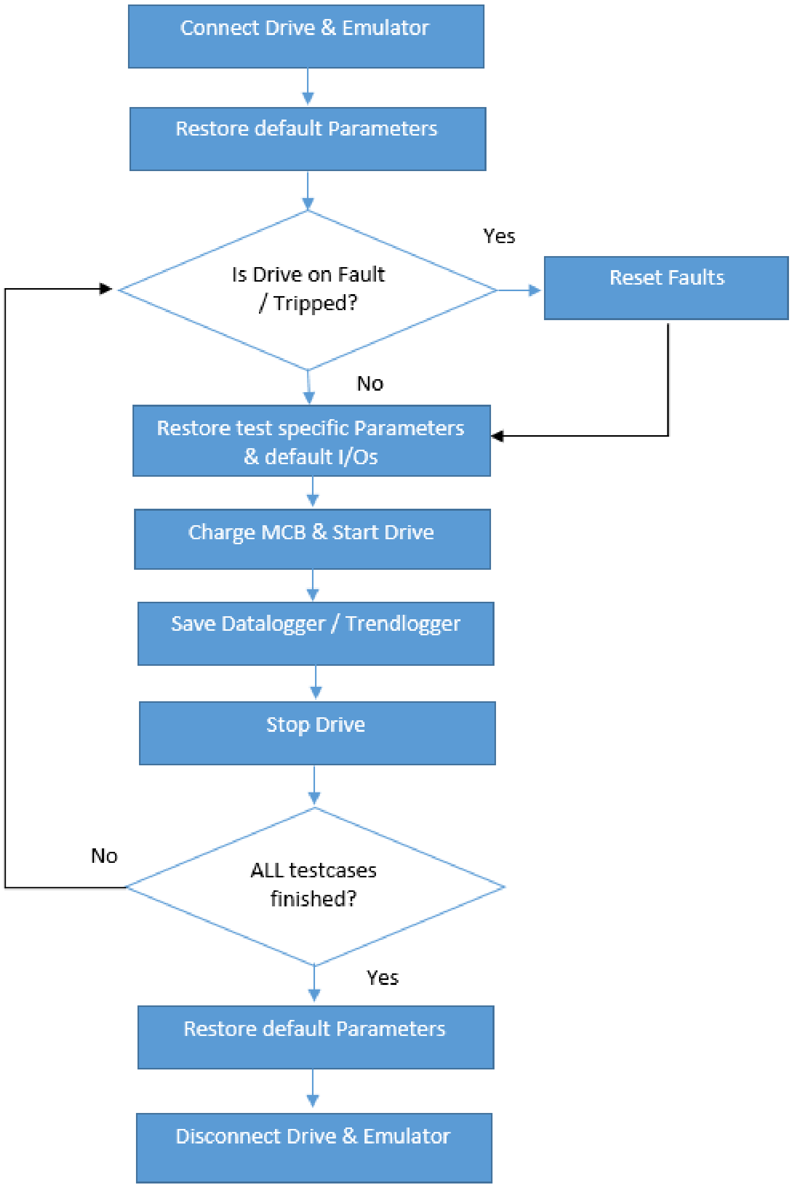

Figure 2.1: Flowchart of Automated Testing Framework

In case if drive is drive is on fault, it is necessary to reset the fault before starting of test case. Trendlogger is a method which stores the testing results with required parameters graph data e.g. motor motor speed, motor current etc to local system.[4]

With parameters initialization & other settings, testing of drive is carried out by Automated testing framework. After running ATF test script, an HTML report is generated with test steps and trending graph. It is possible to automate schedule of test list, Firmware change with latest update & to change environment variable with Jenkins software.

Chapter 3

Hardware in Loop System & Emulator Setup

3.1 Hardware in Loop System

HiL is a kind of real-time closed loop simulation that consolidates the best of the two universes, testing implanted programming software and controllers with real equipment parts to give more practical feedback than any other Simulators.

Closed loop testing gives more precise information and better test inclusion, which implies a superior shot of finding any irregularities prior in the development cycle when it's simpler and less expensive to fix. With HiL testing the plant is supplanted by a recreation of The plant (the HiL test system). On the off chance that the HiL test system is planned well, it will precisely imitate the plant, and can be utilized to test the control system.[1]

With a simulated plant it is conceivable to run tests that would pulverize a genuine plant or would be hurtful for individuals in a genuine circumstance. That is the reason HiL simulation can extraordinarily upgrade the safe task of machines. HiL simulation is more effective.[11][20]

Advantages of HiL Systems:

- HiL system increases Safety
- It enhances Quality
- HiL testing saves Time
- HiL testing saves money as there is no need of actual hardware & other equipment
- It is possible to test & verify the system at failure conditions with HiL systems

Applications of HiL Systems:

- **Automotive systems :** Virtual Vehicle for systems validation and verification, To validate hardware and software automotive solutions.
- **Radar :** For the testing and assessment of the radar framework , Reducing the requirement for flight preliminaries for airborne radar frameworks and field tests for inquiry or following radars.
- **Robotics**
- **Power systems :** For checking operation of electrical systems, stability of networks, HiL helps in developing & simulating the real-time electrical models for Power Systems, Power Electronics & so more. This Real time Simulating platforms provide facilities to develop large scale power systems model for testing & research.
- **Offshore systems :** In Offshore and Marine engineering, control frameworks and mechanical structures are commonly planned in parallel. Testing the control frameworks is just conceivable after integration.[6][7]

3.1.1 HiL setup of Medium Voltage Drive

ABB Medium Voltage (MV) drives offer adaptable and dependable compact design plan for single & also multi motor applications with power extend from 3 to 36 MW extensively. With the end goal to approve the complex converter topologies and control mechanisms of MV drives, a strong & efficient multi core real time test system simulator is utilized for Hardware in Loop (HiL) testing for MV drives.[8]

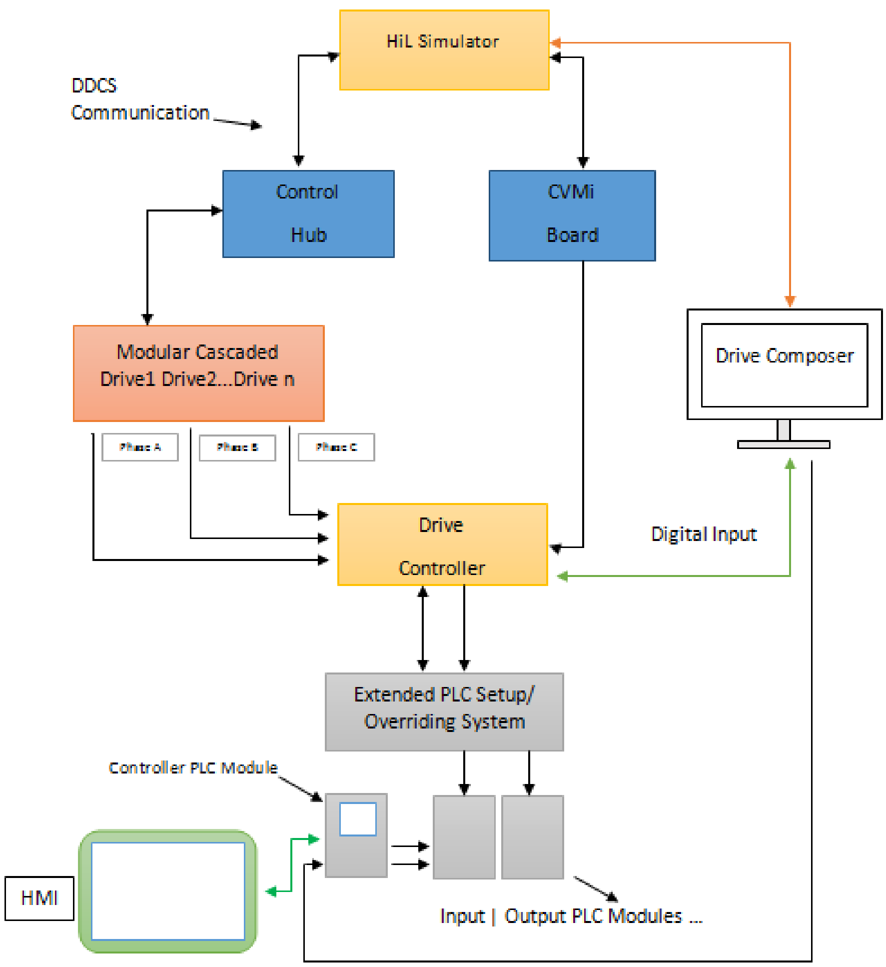

Figure 3.1: Block diagram of HiL system for Medium Voltage Drive

Real Time (RT) simulator consists of highly efficient Central Processing Unit, an adaptable, fast FPGA and signal conditioning boards. As shown in block diagram 3.1, HiL simulator is connected to Control Hub, Current & Voltage measurement [CVMi] board through optical communication link.[13]

As shown in figure 3.2, HiL system consists of Cascaded drive configuration boards, Overriding System, Optical Communication Links to establish faster & secure communication, HMI & so more. HiL simulator acts as combined Power source & Active rectifier unit system with help of OPAL RT hardware & MATLAB simulink models.[20][21]

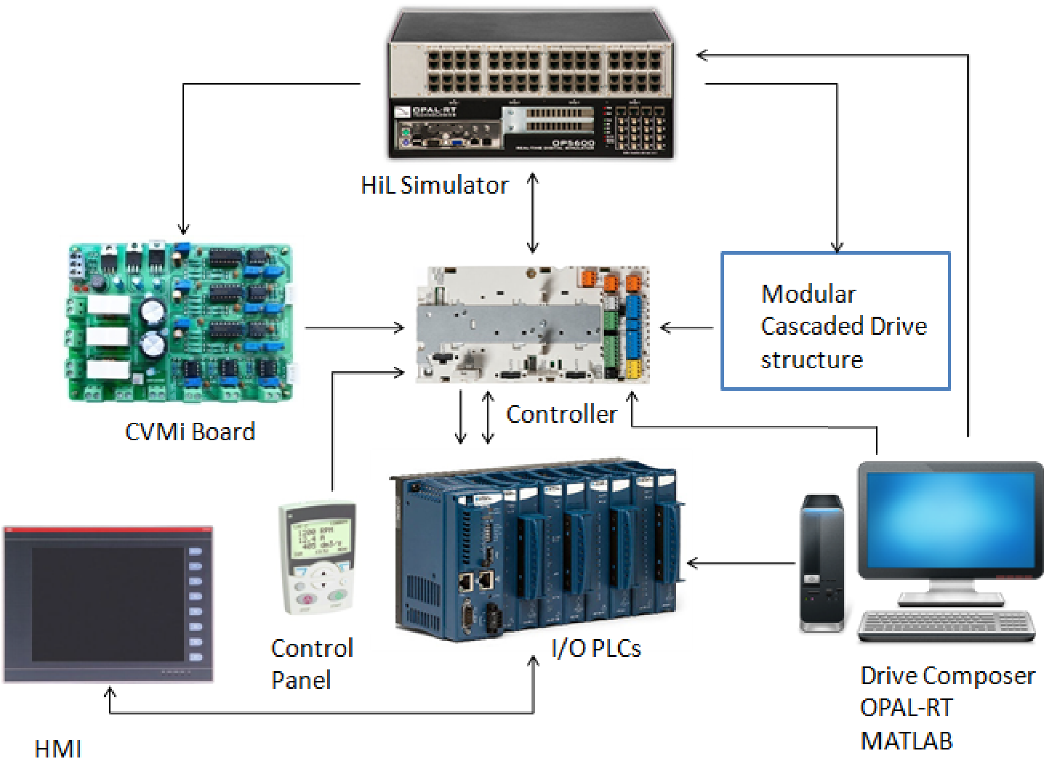

Figure 3.2: Medium Voltage Drive HiL system hardware setup

The multi core Central Processing Unit observes & calculates Medium Voltage drive and drive characteristics continuously throughout the operation. From the control point of view, equipment has Inverter Unit (INU) control card which send the respective gating pulses to inverter dependent on the drive current and DC link voltage input accordingly.[2]

The Simulator test system provides standard connectors like RJ45 for fast observing connections and the back of the test system chassis gives access to these FPGA monitoring connections, all I/O connectors, control link and principle control switch to operate various interlinked broads to it.[22]

3.2 Comparison between HiL & Emulator Setup

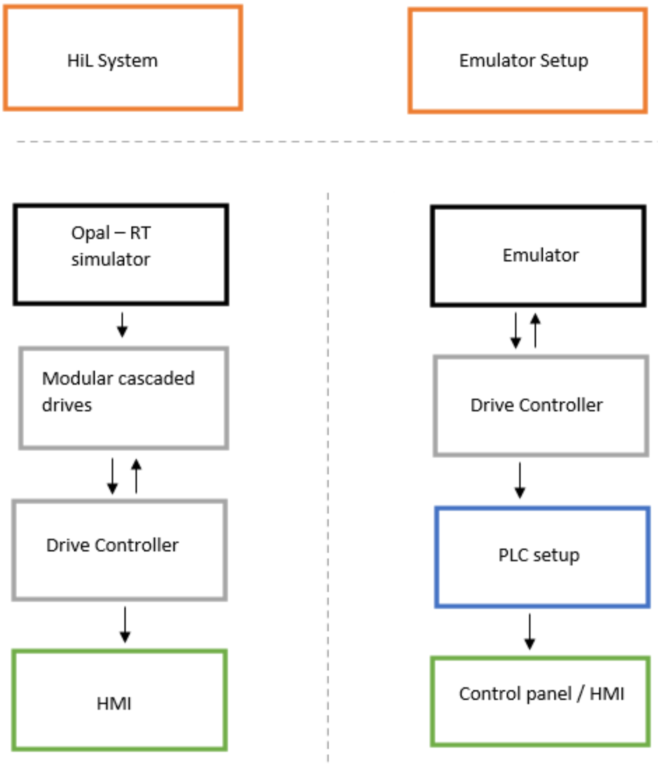

Figure 3.3: HiL & Emulator Setup

Table 3.1: Comparison between HiL System & Emulator Setup

No	HiL Setup	Emulator Setup
1	Complete imitation of Real thing	Mimics a Real thing in Virtual environment
2	Model operates with Real Controls	Simulates most of the parameters
3	Can be performed on Low & high Level	Plant side testing is not possible
4	Able to run Realistic tests	Limited tests comparatively
5	Detailed & Accurate Analysis	Models dont need to be as detailed
6	More Costly	Less Cost & less Maintenance
7	To operate it,detailed Knowledge required	Comparatively less Knowledge required
8	Enhanced scope of testing	Limited scope of testing

3.3 Emulator Setup

It is necessary to test control software before releasing it to market, however it is challenging to test control software on actual drive system as very high cost of drive, space & risk of high voltage is involved. Therefore Emulator controller is developed where a constant DC link voltage & motor currents are given to Drive controller through Emulator controller.[19]

An Emulator setup provides constant DC link voltage & Motor current feedback to the Drive controller. Emulator controller consists of simulated motor model, drive power rating, current feedback and control hub. Required Motor parameters are entered to the Emulator system parameters file e.g. Drive configuration, Drive power rating & other parameters are configured in the Emulator controller.[23]

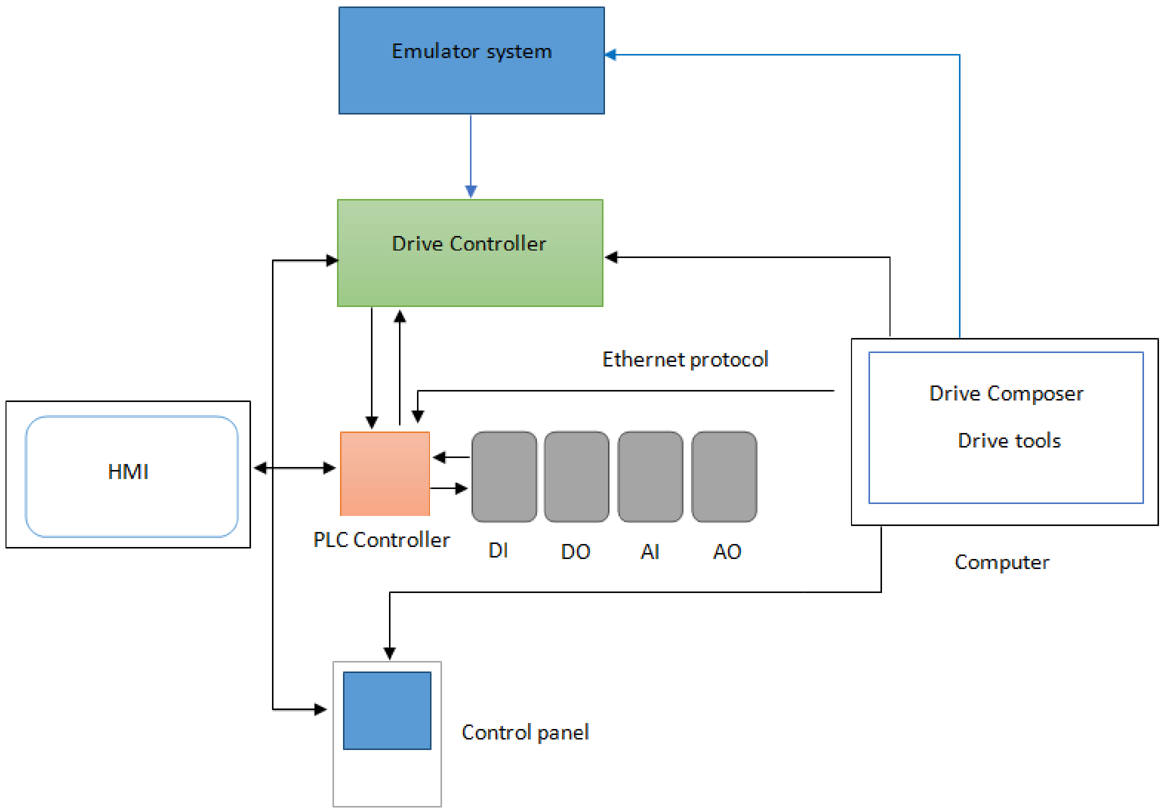

Figure 3.4: Emulator setup for Medium Voltage Drive

As shown in above figure 3.4, it is simplified diagram of Emulator setup. In Emulator setup, it contains Emulator which is controller similar to Drive system. Drive system is configured in such a way that drive can be operate through Remote mode of operation, Control Panel or HMI & computer also.

Emulator setup contains Plant side parameters like Grid parameters such as grid current & DC Voltage, Transformer winding temperature, phase currents, phase voltages, Active current & Reactive current limits, Grid Power, user defined parameters & so on.[24]

A Virtual testing environment is created where Controller behaves like Real time field conditions. For drive external control it is necessary to use overriding system example PLC using OPC control Setup & National Instruments setup.

Object Linking and Embedding (OLE) for process control (OPC) is a set of standards developed by a joint collaboration of leading automation industry suppliers. OPC's primary mission is to define a uniform interface for use with any organization OR Custom software package.[1]

As shown in block diagram of Emulator setup, it mainly consists of Plant Controller as well as Drive Controller which are connected to each other by Optical Communication link via DDCS Adapters. There is communication between Computer & Emulator setup by Communication Adapter. There is Overriding System setup is present to control drives connected to it. Emergency Protection circuit is also provided to setup.[18]

Chapter 4

Testcases & Results

4.1 Testcase - Drive Status Word Bits

4.1.1 Description:

Drive status words provide bits status with which it is easier to analyze test report. Main objective is to check drive behavior in terms of status throughout operation. This test checks the functionality of Drive Status Word Bits status.

Drive status word incorporates various status bits such as Motor Started bit, DC Charged Bit, Tripping Bit, Following reference, Ready to start bit, Ready Run bit, Local Control bit, External control bits, Limiting bit and so on.

4.1.2 Test steps:

Here Drive status bits are Speed control bit, DC Charged bit, Following reference bit, Started bit & Tripped bit. As attached in figure 4.1 of ATF test result, drive is started with speed reference of 500 RPM & -350 RPM respectively. Motor follows speed reference and reaches set reference speed with defined acceleration time. As drive discharge command is given to the drive, it discharges and motor speed becomes 0 RPM.

4.1.3 Testdata table:

For this testing, testdata is shown in table 4.1 as follow:

Table 4.1: Drive Status word observation table

No	Parameters	Result
1	Motor Rated Speed	1500 RPM
2	Speed ref	500 RPM, -350 RPM
3	DC Voltage	1 KV
4	DSW Bits	Started bit, Following Ref bit
5	MSW Bits	Tripped bit
6	Other Bits	Speed control bit, DC charged bit

In this test, Drive status word bits are Started bit & Following reference bit. While Main status word bit is Tripped bit. Other bits are DC Charged bit & Speed control bit.

Motor speed range is -1500 RPM to 1500 RPM. DC voltage is 1 KV & Motor speed references are as given in table 4.1.

4.1.4 Test Result: Drive Status Word bits

Test setup used : Emulator system

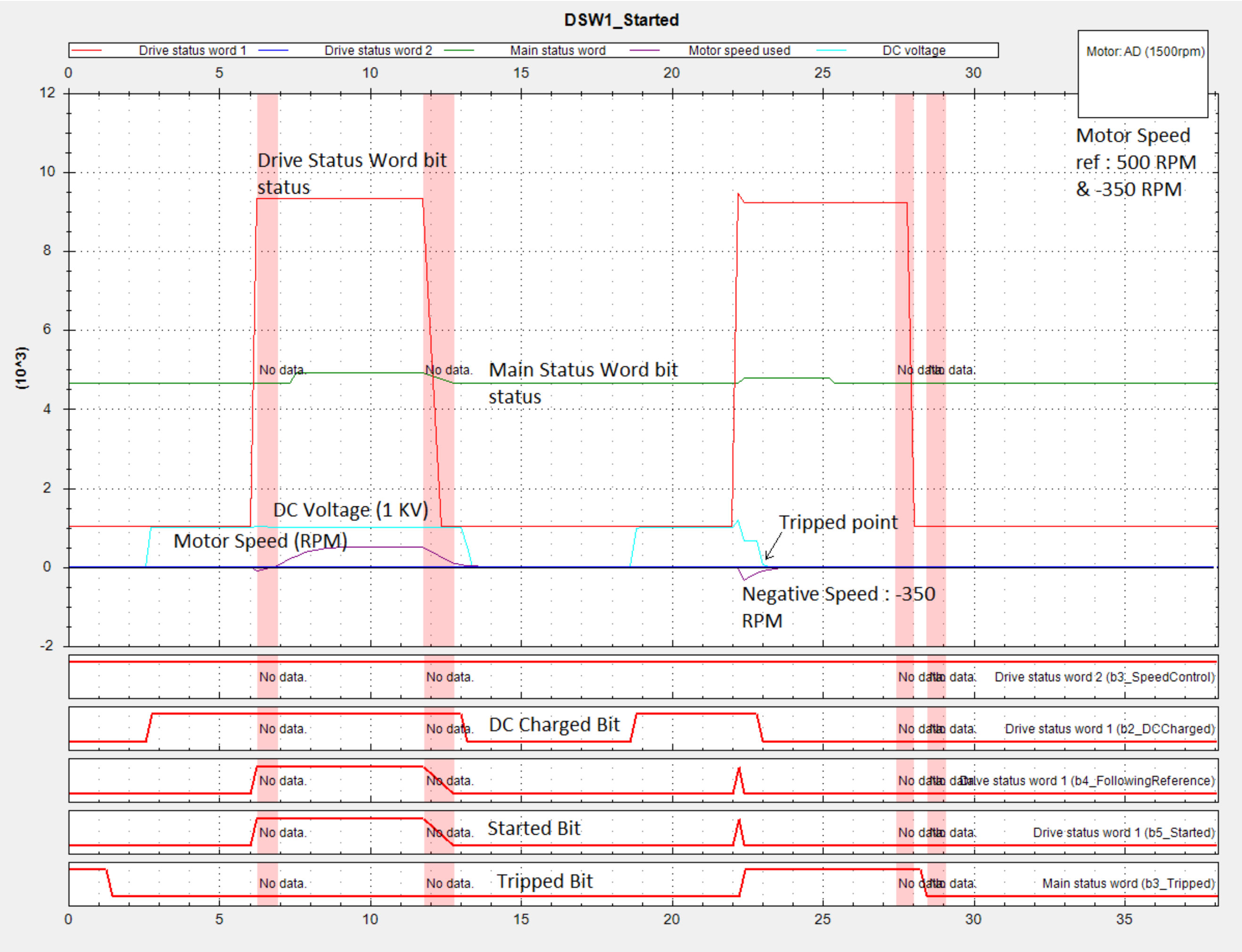

Figure 4.1: Automated Testing result - Drive Status Word testcase

As shown in Figure 4.2, it is Automated testing result of Drive status word. Here motor speed ref is 500 RPM & -350 RPM respectively. Result is shown with plotting various Drive status bits & Main status word bits.

As shown in result, drive charges and starts following speed reference, hence DC charged bit, Following reference bit and motor started bit goes HIGH. When drive has fault conditions, there is Tripped bit status HIGH.

4.1.5 Test Validation:

Asserts are methods which give validations whether performed test is correct or there are bugs in it. Asserts set conditions, if test correctly follows then it passes otherwise it will fail.

Figure 4.2 represents ATF test report which is generated after test completion & test-case is correctly working hence showing green status in report.

Figure 4.2: Drive Status Word HTML test report

In testcase, asserts are included with testcase such as motor actually started or not with started bit assert, motor tripping status, Following speed reference validations.

4.2 Testcase - Load Analyzer Test

4.2.1 Description:

Load analyzer testcases collect amplitudes of selected signal & these collected signal amplitude samples are allocated into 10 parameters. Each of parameters represent amplitude range of 10%. Total collected amplitude samples will be 100% only. Main objective to perform this testing is to monitor motor parameters & to log parameter peak values throughout interval.

In this testcase, user can select various signal like DC voltage, Motor speed used, Supply frequency, Motor current & many more, where signal is to be monitored by a logger. The logger records values of the signal along with time & following data is also gathered.

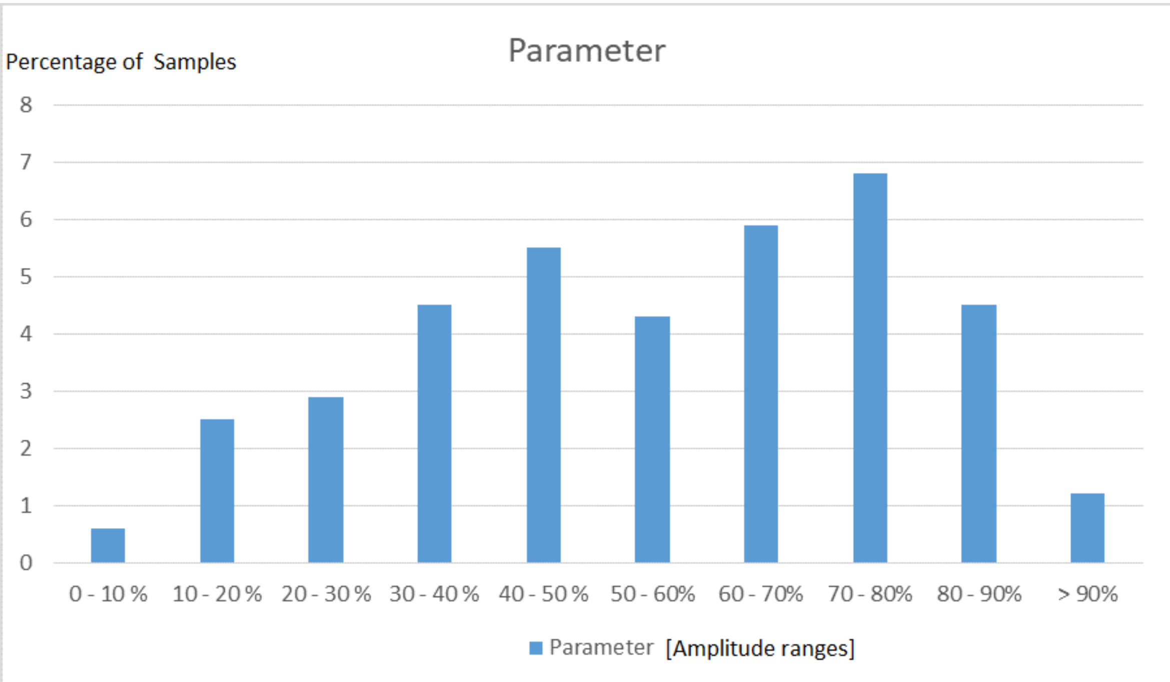

Figure 4.3: Amplitude Logger graph

Amplitude logger test is carried out on drive for certain duration, after test completion user can know speed variation in different time duration & analyze results effectively. With peak value logger it is possible to capture selected parameter's peak value at time.

4.2.2 Applications:

In applications where user wants to monitor motor parameters change within operation interval, in such case amplitude logger functionality is useful. Amplitude logger represents the amplitude of user selected signal in % form throughout drive operation.

If motor is running with various speed references & customer wants to confirm motor current operating range then amplitude logger functions are useful. Amplitude logger testcases are useful in application such as Assembly lines in industrial processes where assembly lines run at various speeds for products.

4.2.3 Test steps:

For Amplitude logger test of Medium voltage drive, as a signal to be monitored "Motor speed used" is selected. By starting the drive & applying certain speed reference to it, Amplitude logger result can be obtained as mentioned in manual result figure 4.4.

Speed variation during testing in different time duration can be observed by Speed percentage slots which are changing as shown in figure 4.4 Amplitude Logger.

In similar way after certain interval, Speed is reduced from rated speed & variation in Amplitude logger can be observed in result as shown in figure 4.4 Amplitude Logger. Here in this testcase, Maximum Speed limit & Minimum Speed limit are 1500 RPM & -1500 RPM respectively. Acceleration time is 5 sec & Deceleration time is 10 sec.

4.2.4 Test Result: Load Analyzer

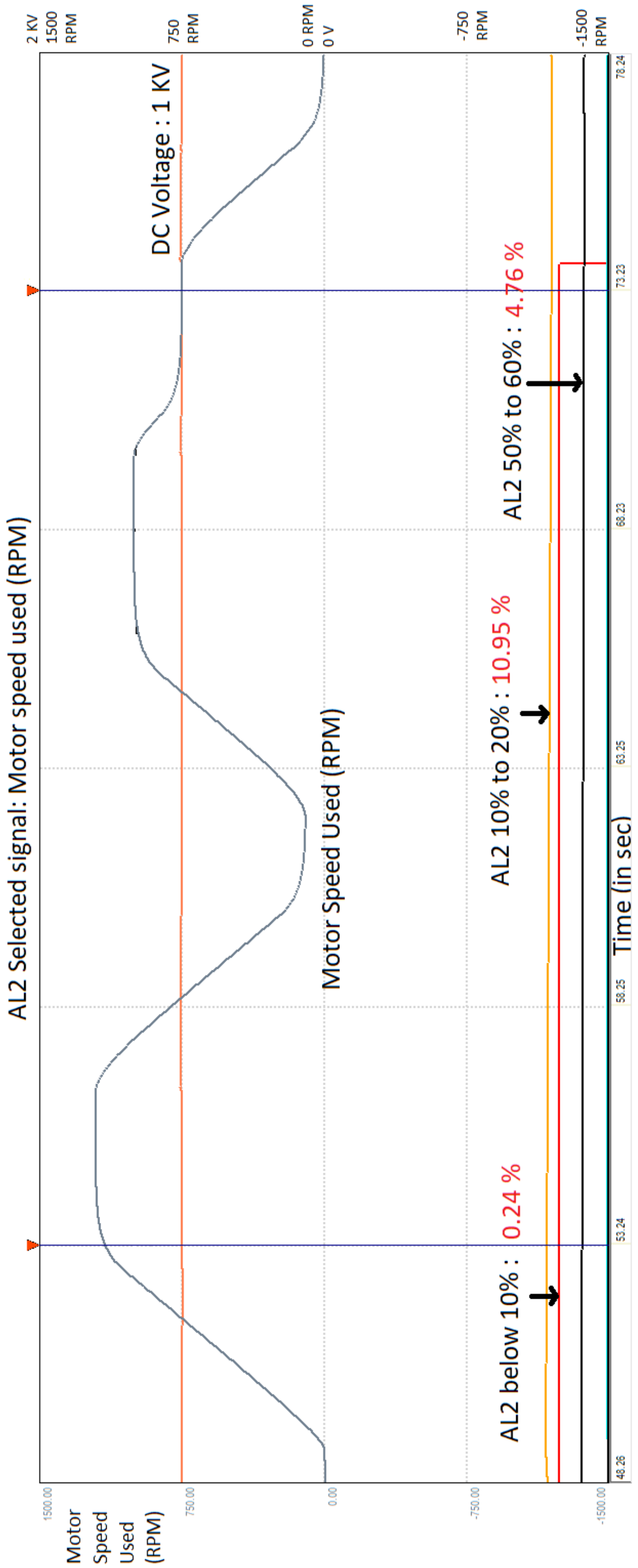

Figure 4.4: Manual Testing Result-Amplitude Logger testcase

As shown in above result 4.5 after starting the drive with charging MCB commands, Speed of drive is increased to 750 RPM from initial 0 RPM. With it logger records variation in motor speed to corresponding speed percentage. Table in figure 4.5 Amplitude logger Parameter table data is showing parameters observed during test execution.

	Pen	Visible	Mask	Y-scale	Min	Max	y1
Motor speed used (rpm)		☑	FFFFFFFF	☑	-1500.00	1500.00	1148.41
DC voltage (V)		☑	FFFFFFFF	☑	-2000.00	2000.00	1000.10
AL2 below 10% (%)		☑	24	☑	0x0	0xFF	0x24
AL2 10 to 20% (%)		☑	FFFFFFFF	☐	0.00	100.00	10.95
AL2 20 to 30% (%)		☑	FFFFFFFF	☐	0.00	100.00	0.32
AL2 30 to 40% (%)		☐	FFFFFFFF	☐	0.00	100.00	0.08
AL2 40 to 50% (%)		☐	FFFFFFFF	☐	0.00	100.00	0.16
AL2 50 to 60% (%)		☑	FFFFFFFF	☐	0.00	100.00	4.76
AL2 60 to 70% (%)		☐	FFFFFFFF	☐	0.00	100.00	1.11
AL2 70 to 80% (%)		☐	FFFFFFFF	☐	0.00	100.00	0.24

Figure 4.5: Observation table-Amplitude Logger

Test setup used : Emulator system

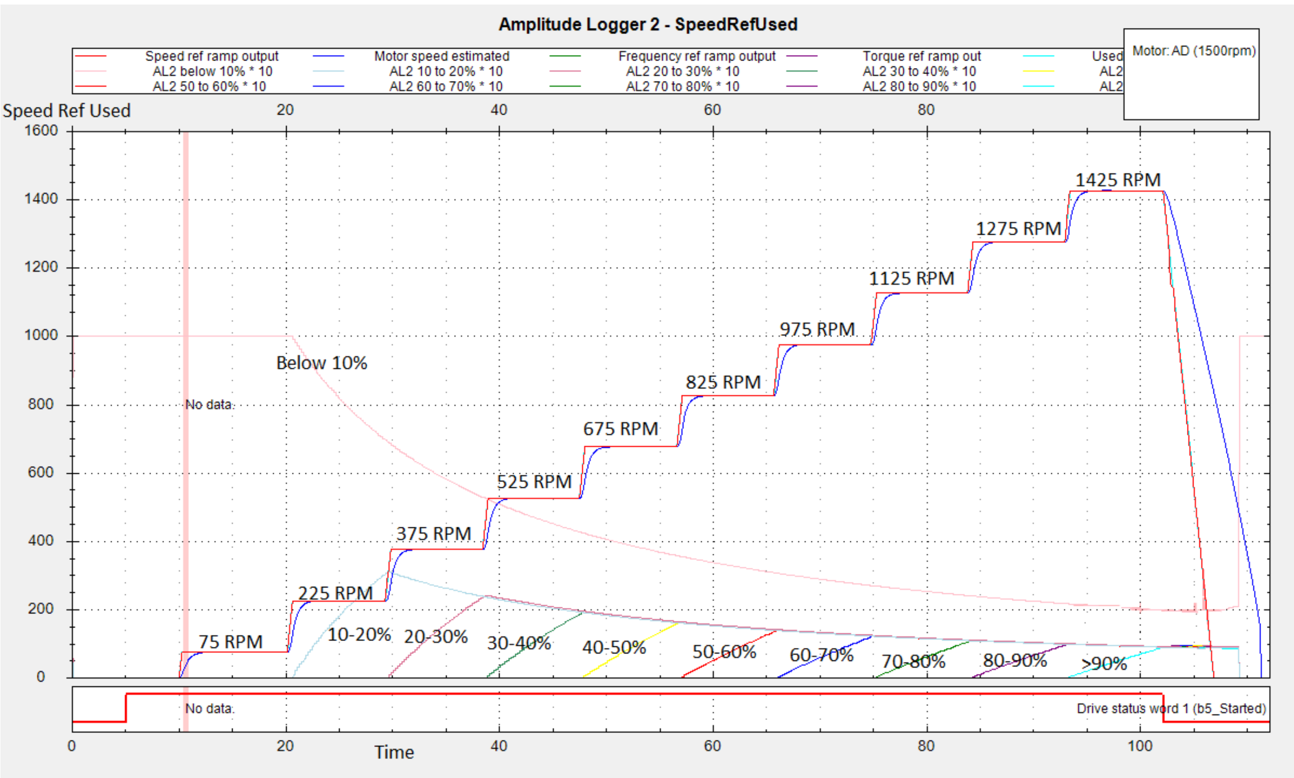

Figure 4.6: Automated Testing result - Amplitude Logger testcase

Figure 4.6 represents the automated testing result of Amplitude logger test. In this case, Amplitude logger monitors motor speed used signal during testing. There is change in motor speed reference from 75 RPM to 1425 RPM throughout testing interval, hence corresponding Amplitude logger can be observed from result 4.6.

4.3 Testcase - Jogging functions

4.3.1 Description:

Jogging functionality is helpful during maintenance & commissioning of drive at low speed operations. Jogging belongs to control parameters of drive. In Jogging functions, when jogging signal is activated drive follows defined motor speed reference. Jogging functions consist of various testcase such as:

- Jogging Control Mode
- Emergency Jogging
- Jogging functions through IO commands
- Jogging Priority IO

Jogging control mode will verify speed & also check Jogging 1 & Jogging 2 in Local Mode. This test verifies the External Control Mode (Ext1/Ext2) functionalities and operation modes such as Speed, Torque, Minimum, Maximum & Add jogging functions normally.

Here Jogging functions consist of Jogging Emergency stop testcase & Jogging Priority test. To check if emergency stop command works correctly when jogging is enabled, Emergency jogging test has been carried out. While Jogging priority testing has been performed to confirm Jogging source priority.

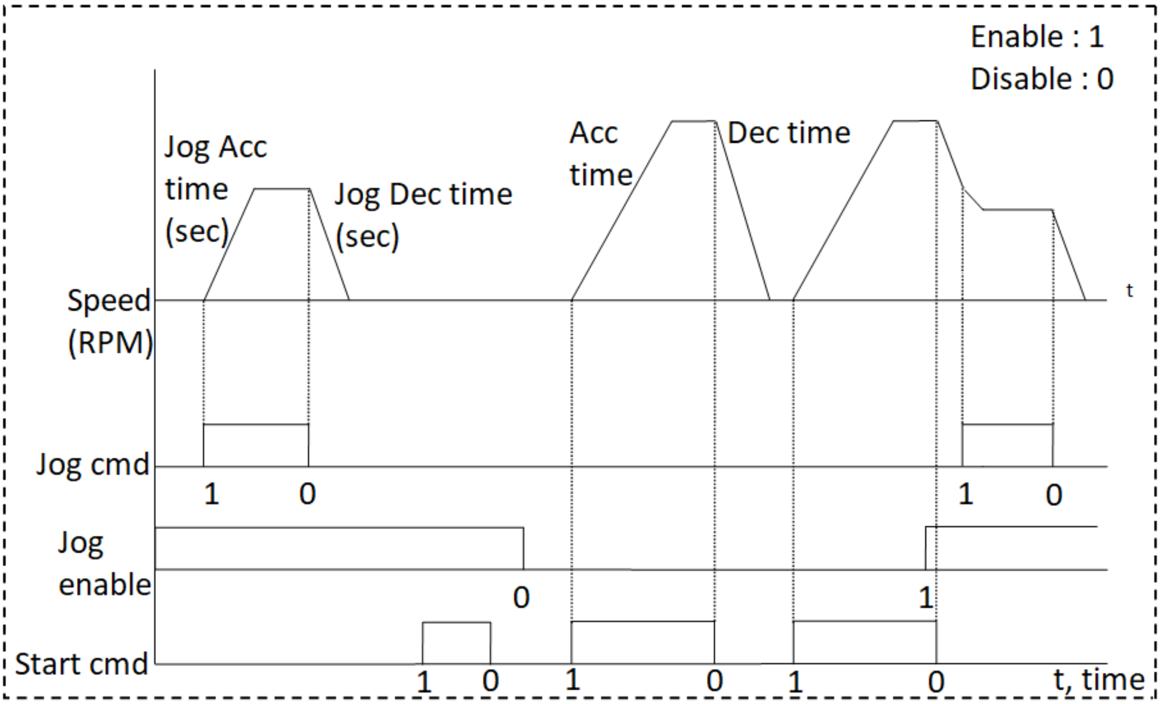

Figure 4.7: Basic diagram of Jogging with Jog cmd

Above diagram 4.7 is representation of operation of drive under Jogging functions. There are various commands are mentioned in diagram such as Jog Enable, Jog command, Start command & plotted effects with Speed. These Jogging commands & start command are explained as below:

- Jog command acts as a source of Jogging, for ex. Jogging 1 start source
- Jog enable selects source for jog enable & Jogging is enabled
- Start command is for drive start command changes

As shown in above diagram, "Jog enable" is selected HIGH to enable jogging function. As "Jog enable" is present, it is possible to run drive with "Jog cmd". User has to define certain parameters before running drive in Jog mode e.g. Jog reference, Jog source, Jog Acc time, Jog Dec time & so on. In jogging enabled mode drive follows Jog reference, Jog Acc & Dec time instead of Speed reference, Acc & Dec time respectively.

When Jogging is applied on motor, there is no significance of start command. It is observable from above diagram that when start command is present, start command must be removed before applying jogging enabled.

4.3.2 Applications:

Jogging is helpful in getting direction of rotation, to get a coupling in correct position or for alignment purposes. It is used during maintenance & commissioning of drive at low speed operations.

With Jogging functions, user can run motor for few seconds in applications such as material handling, motion control, moving crane to a particular location & so more.

4.3.3 Test steps:

To check if emergency stop command is working correctly with Jogging functions this testing is carried out on Emulator system. Jogging emergency confirms that the drive does not start automatically after the Emergency input is removed and the jogging enable and jogging command are true.

In Jogging emergency function, first jog start command is selected for e.g. Inching 2 (jog2) as shown in result 4.8. Enable Jog command & start the drive with jog reference. As emergency stop signal is applied to motor, DC voltage will discharge & motor speed reaches 0 RPM. Similar test is repeated with various speed reference & jog source commands.

In Jogging priority testing, tester will check priorities of jog commands when both jog sources are applied to motor. There are two jog source commands as Jog1(inching 1) & Jog2(inching 2). If jog1 is enabled with jog reference 1, motor will follow only jog ref1 speed & even though jog2 is enabled it will be neglected.

4.3.4 Test Result: Jogging Emergency function

Test setup used : Emulator system

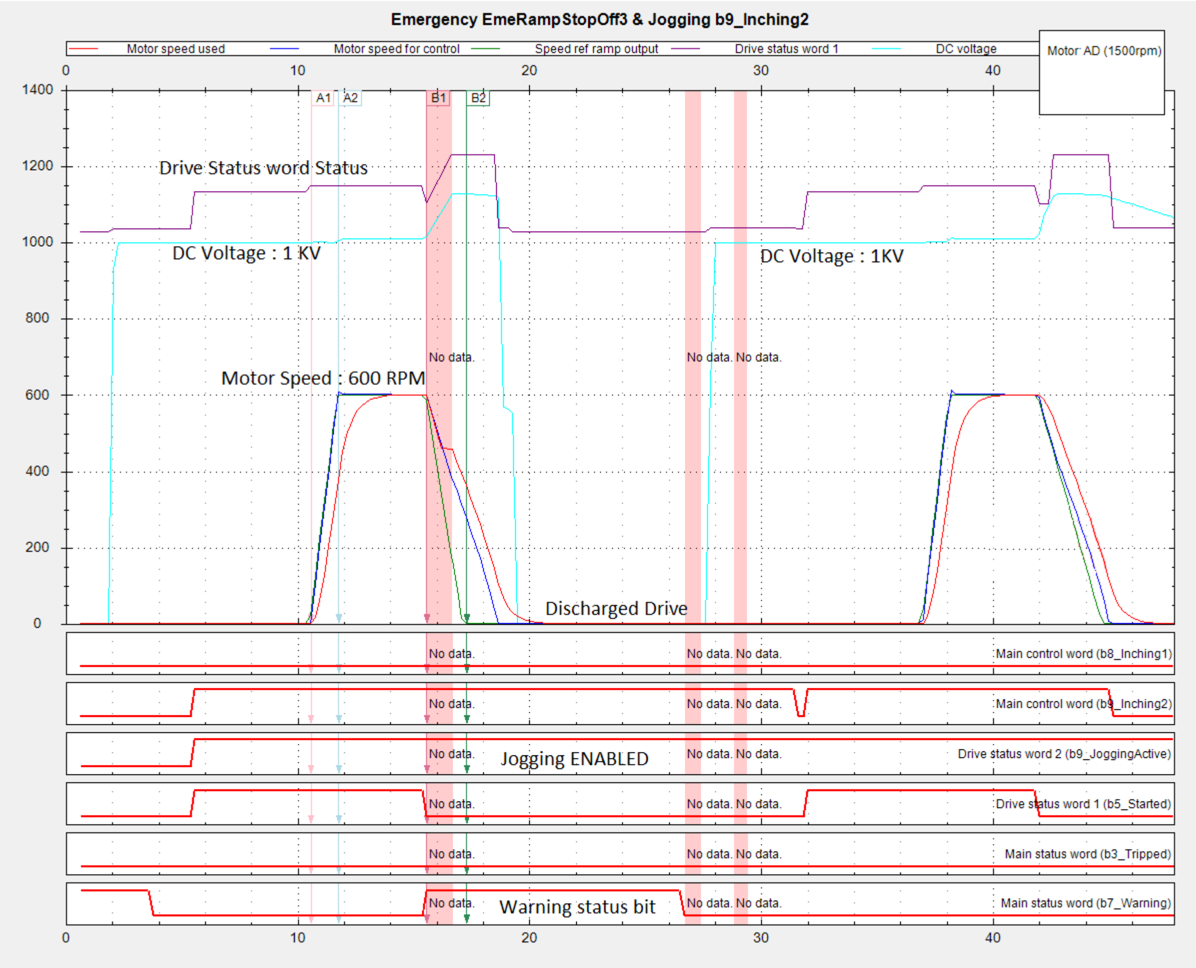

Figure 4.8: Automated Testing result - Jogging Emergency test output

In figure 4.8, it is observable that there are motor speed reference as 600 RPM & Jogging is enabled throughout testing. Jogging emergency is properly operating with emergency stop command without any fault conditions.

Results are attached to report after manual & automated testing on Emulator system. Automated Testing with HiL setup also can be performed in similar manner for Jogging functions.

4.3.5 Test Result: Jogging Priority function

Test setup used : Emulator system

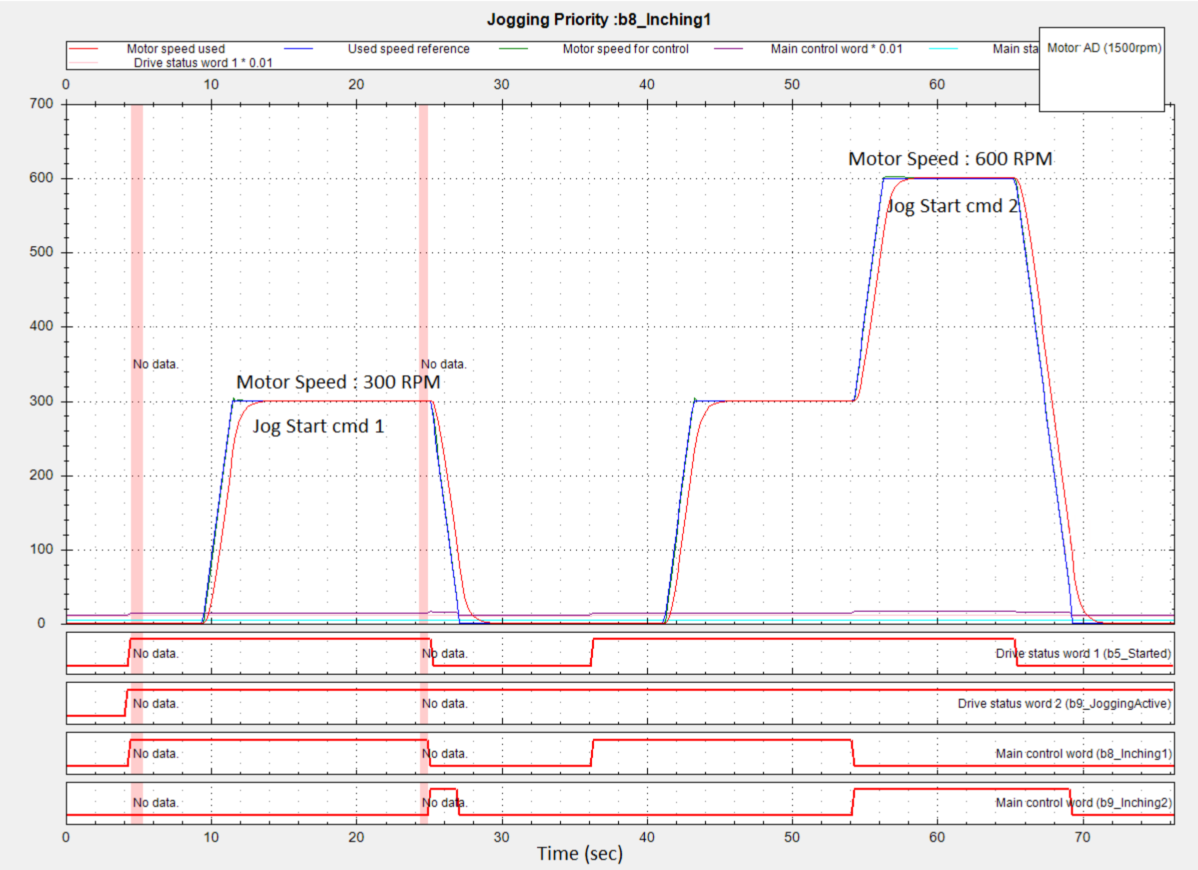

Figure 4.9: Automated Testing result - Jogging priority functions

Above mentioned result in figure 4.9 belongs to Jogging priority Automated testing result. Jogging emergency confirms that irrespective of the commands given via FieldBus or via I/O's has no effect on the jogging.

As shown in test output Jogging has started with Jogging Start cmd 1 and Jogging Start cmd 2 is also activated though the jogging continues with the Jogging Start cmd 1 and neglects Jogging Start cmd 2.

4.4 Motor Overcurrent Fault Test using HiL System

4.4.1 Description:

A power system is very sensitive to any types of faults either due to natural disasters or due to disoperation of the system. So it is extensively required to perform protection testing on any electrical system & equipment to avoid permanent damage to power system components leading to considerable costs, which is not desirable at any cost.

Motor overcurrent fault testing of medium voltage drive is carried out using Hardware in loop setup manually. In it, testing is carried out on HiL setup along with OPAL-RT software which is interfacing with HiL setup.

Motor overcurrent fault belongs to one of protection functions. It is necessary to perform protection testing on HiL system as HiL is providing plant side parameters access which are fixed or not accessible in case of Emulator system.

4.4.2 Test steps:

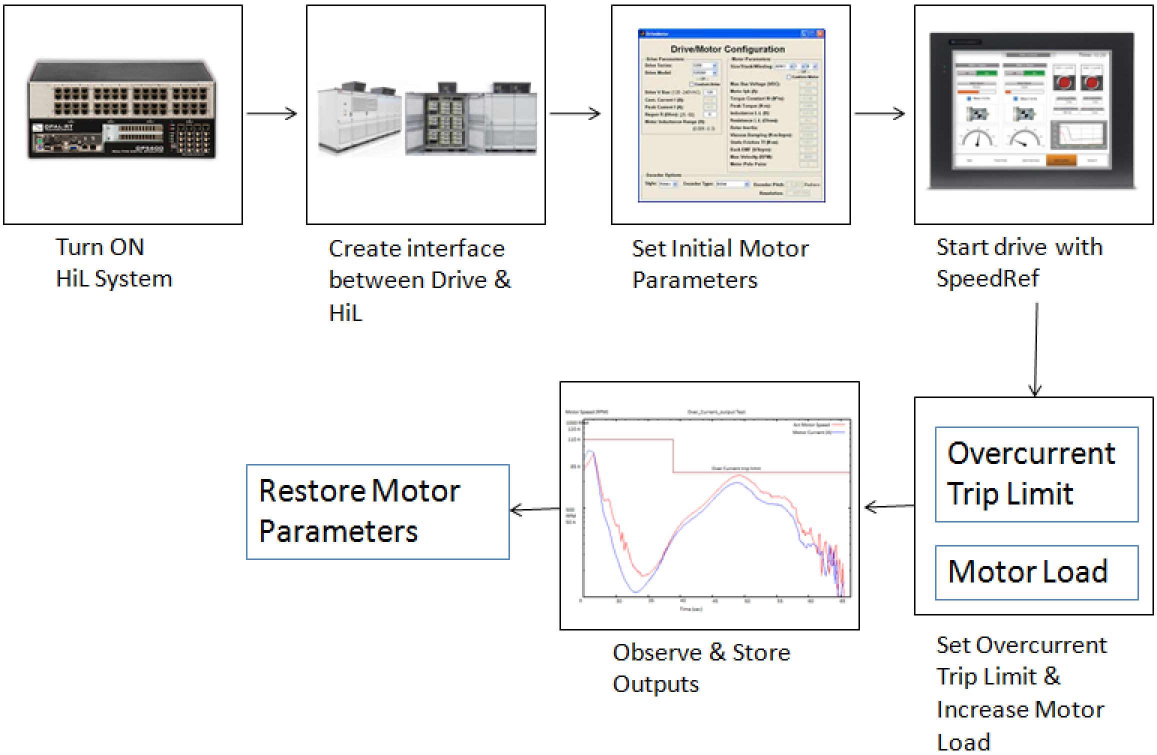

Figure 4.10: Motor Overcurrent Fault Test Steps

In figure 4.10, it is a diagram of Motor Overcurrent fault test steps to perform HiL testing. Hardware in loop system is connected to drive controller hence, first step is to make drive fault free & to set initial motor parameters for e.g. motor nominal current, motor nominal voltage, motor nominal speed, motor nominal frequency, motor nominal torque user and so more.

After setting motor parameters, drive starts with speed reference & motor overcurrent trip limit has been changed such that motor actual current (A) is greater than motor overcurrent trip limit. There will be motor overcurrent fault in drive composer & drive will discharge.

4.4.3 Test Result: Motor Overcurrent fault test

Test setup used : HiL system

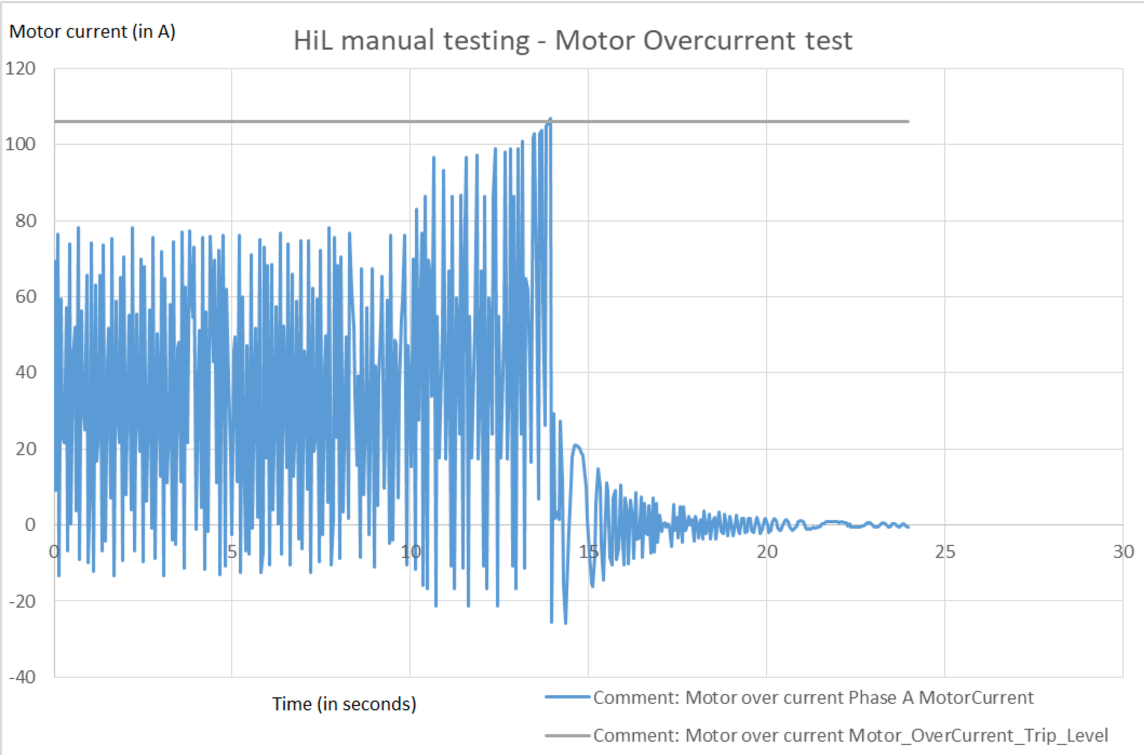

Figure 4.11: HiL Setup - Motor Overcurrent Fault Test result

In figure 4.11, it is motor overcurrent fault test output with overcurrent trip limit of 106 A. In motor overcurrent manual testing, drive is started with reference speed of 500 RPM. Before starting the drive, motor overcurrent trip level has been set as 106 A, now motor reaches the rated speed & nominal current at instant is 67 A.

As shown above in figure 4.10 motor overcurrent fault test result, as motor current exceeds the trip current limit actual motor current reduces to zero within 8 seconds.

To test the overcurrent testing, external load is applied on motor, hence there is increase in motor current which can be observed by result. When motor phase current exceeds the overcurrent trip limit, "Overcurrent fault" occurs, drive discharges & motor current reduces to zero. At instant motor current trip counter also tends to zero.

4.5 Testcase Energy Optimization

4.5.1 Description:

This test checks energy optimization function. Energy optimizer function decreases motor actual flux hence there is subsequent changes in energy consumption & motor noise level.

As actual flux is directly proportional to output voltage of drive, motor output voltage changes directly as there is change in flux of drive. This test is carried out using Scalar control mode with Local operating mode of drive.

This testing is applicable to linear load only, it is not applicable to constant load applications.

4.5.2 Applications:

Energy optimization function helps in below mentioned applications to achieve optimum energy efficiency below rated load conditions.

- HVAC Fans
- Pumps(no load)

4.5.3 Test steps & observation table:

In this test, drive starts with certain speed reference & operates below rated load. When drive is achieving rated speed reference, Energy optimizer function is inactive in beginning. As Energy optimizer function is Enabled, trendlogger starts recording corresponding changes in below mentioned motor parameters.

Table 4.2 is observation table of energy optimizer testing with "Enabled" & "Disabled" Energy optimizer function.

Table 4.2: Energy Optimization observation table

No	**Energy Optimizer : Enabled**	**Energy Optimizer : Disabled**
1	Motor speed = 1001 RPM	Motor speed = 1000 RPM
2	Motor current = 0.60 A	Motor current = 1.29 A
3	Motor Flux actual = 50 %	Motor Flux actual = 100 %
4	Output frequency = 33.77 Hz	Output frequency = 33.77 Hz
5	Output voltage = 122 V	Output voltage = 241 V
6	Output Power = 0.05 KW	Output Power = 0.09 KW

From manual testing results of energy optimization test, it is observable that as energy optimizer function has been enabled, there is reduction in Motor current %, Motor Output voltage & Output Power (KW) without changing motor actual speed.

4.5.4 Test Result: Energy optimizer testing

Test setup used : Emulator system

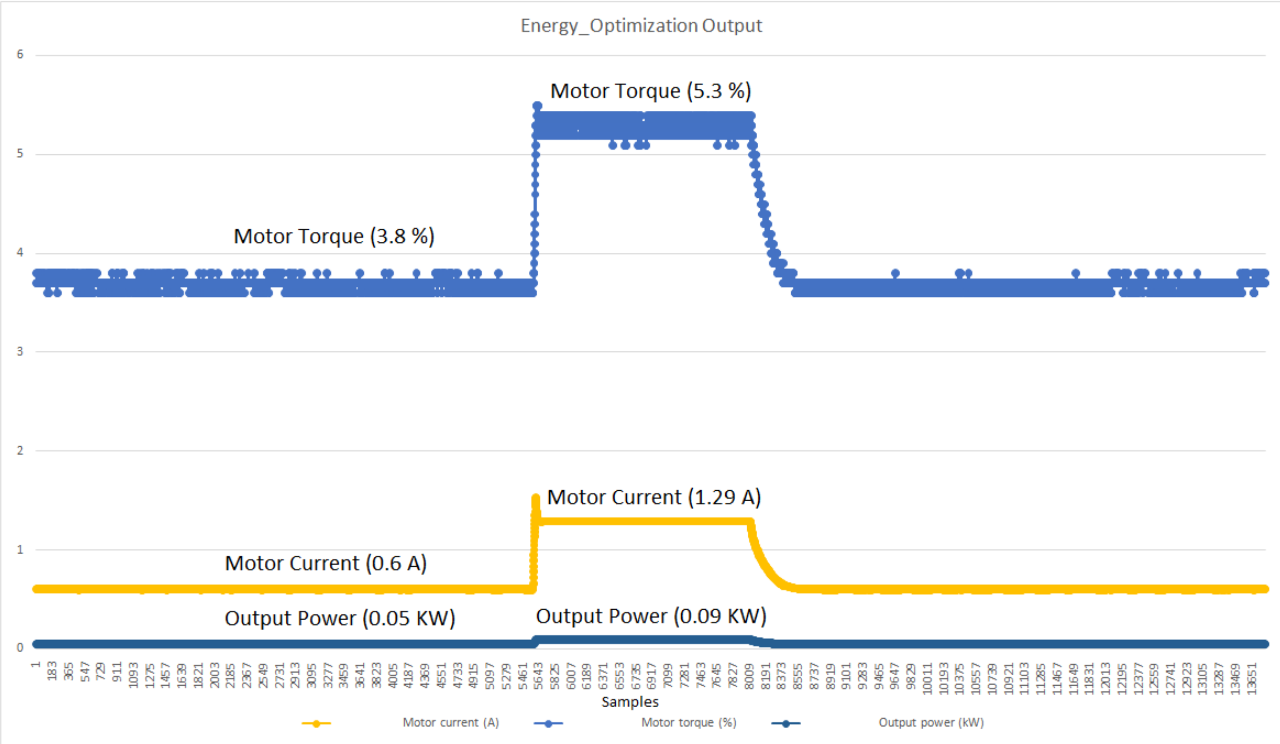

Figure 4.12: Test Output with Motor Current & Motor Torque variations

As shown in figure 4.12, it is corresponding result of Scalar control mode in Local operating mode. In result 4.12, motor speed is 1000 RPM & flux reference value is 100% in disabled energy optimizer function.

Above test result represents output with Enabled & Disabled Energy Optimizer conditions. Motor parameters such as Motor current(A), Motor Torque(%) & Output Power(KW), Flux actual % are shown in test results 4.13 & result 4.14.

Test setup used : Emulator system

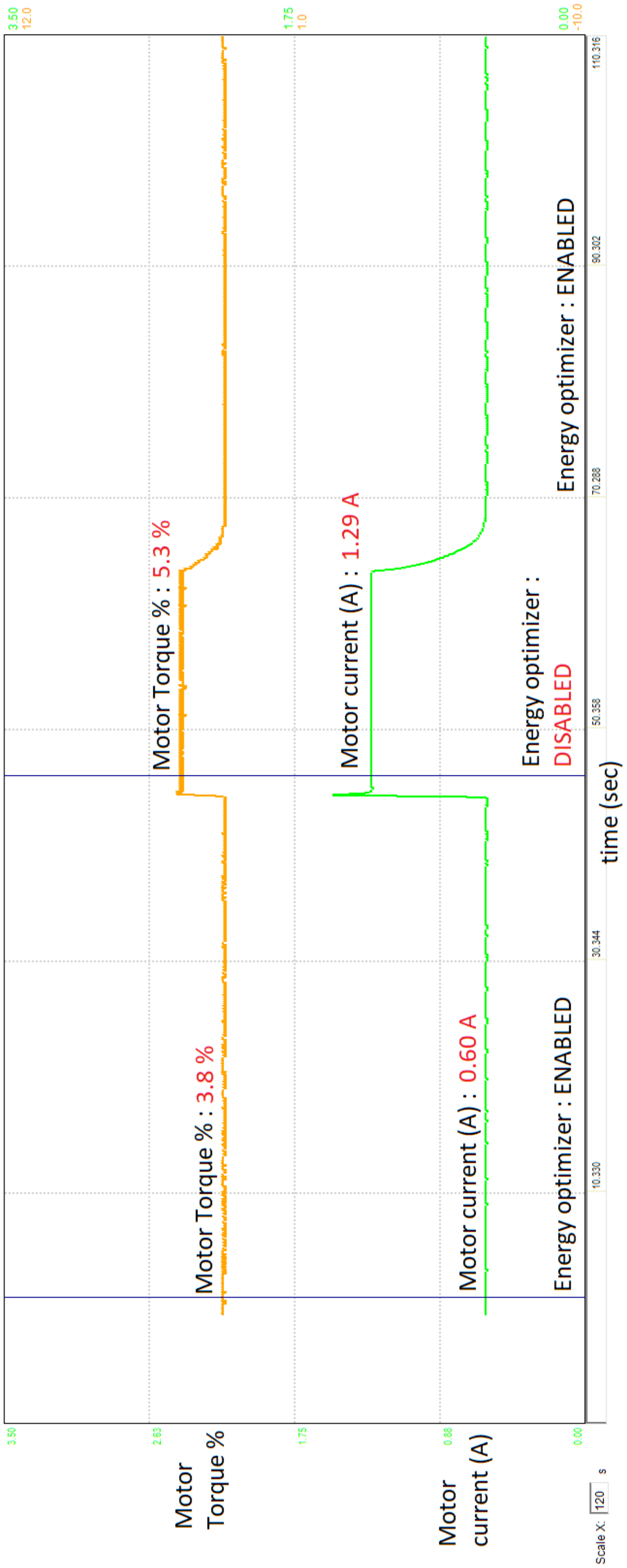

Figure 4.13: Manual testing of Energy optimization in low voltage drive

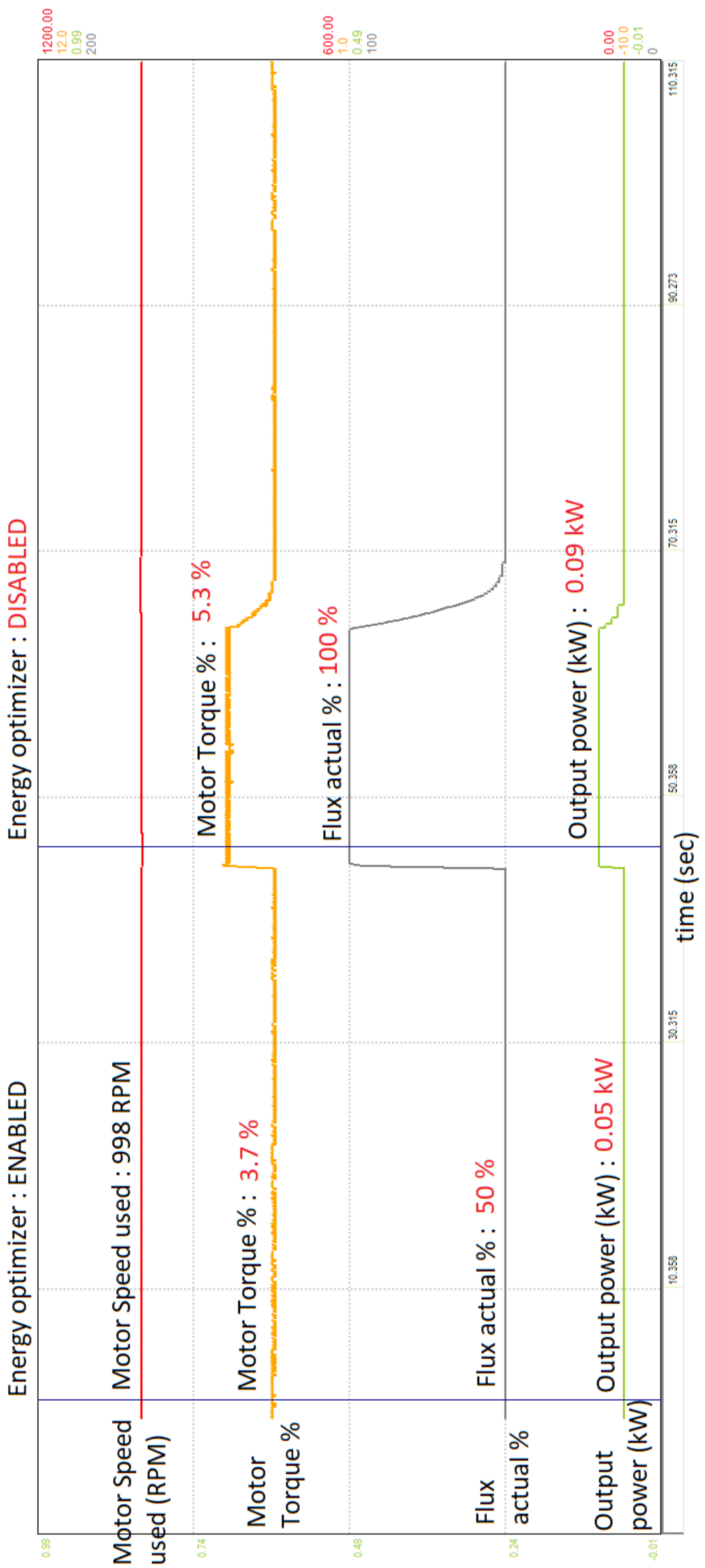

Figure 4.14: Manual testing of Energy optimization in low voltage drive

As shown in above figure 4.13 & figure 4.14, it is manual testing result of energy optimizer function in Low voltage drive. Figure 4.15 represents drive parameters with outputs & Observation table for Enabled & Disabled Energy optimizer function is given in table 4.2.

Name	Pen	Visible	Mask	Y-scale	Min	Max	y1	y2
Motor speed used (rpm)		☑	FFFFFFFF	☑	0.00	1200.00	1000.02	998.53
Output frequency (Hz)		☑	FFFFFFFF	☑	0.00	90.00	33.77	33.45
Motor current (A)		☑	FFFFFFFF	☑	0.00	3.50	0.60	1.29
Motor torque (%)		☑	FFFFFFFF	☑	-10.0	12.0	3.7	5.3
Output voltage (V)		☑	FFFFFFFF	☑	0	300	123	243
Output power (kW)		☑	FFFFFFFF	☑	-0.01	0.20	0.05	0.09
Flux actual % (%)		☑	FFFFFFFF	☑	0	200	50	100

Figure 4.15: Energy Optimization drive parameters

4.6 Testcase User Load Curve Functions

4.6.1 Description:

User load curve functions help to monitor motor parameters & to take appropriate actions like fault or warning actions if selected parameter exceeds predefined load curve. User load curve can be useful in conditions for e.g. to monitor pressure & pump has been blocked by matter, motor shaft choking due to faults or overload, motor load being lost because of snapping of a transmission belt & so on.[25]

In Medium voltage drive, there is User load curve function to monitor certain Motor parameters such as Motor current % , Motor Torque, Motor speed throughout given operation region with respect to time & defined Underload & Overload points. There are below mentioned User load curve testcases as:

- ULC Supervision Signal Selections
- ULC Motor Current % with User Load Points
- ULC Motor Current % with Actual Load changes

In User load curve testcase, user selects Under load points & Over load points to define operation region with Speed table points. In this testcase Speed table points, UL points & OL points are as mentioned in below table. Instead of predefined Speed table points, user can select various speed points according to drive applications.

Table 4.3: User Load Curve : Underload points & Overload points

No	Speed Table Points	Under Load Points	Over Load Points
1	200 RPM	24 %	40 %
2	400 RPM	25 %	40 %
3	600 RPM	30 %	45 %
4	800 RPM	28 %	45 %
5	1000 RPM	30 %	40 %

In above table 4.3, various Overload points & Underload points are defined to corresponding Speed table points. For speed below 200 RPM & speed above 1000 RPM, User status output does not generate overload limit warning or underload limit warning.

As shown in graph 4.16 User load curve graph for motor Speed v/s motor Current %, there are user defined UL points & OL points as mentioned in corresponding table of speed table points. These UL points & OL points form operating region for drive. In this case, supervision signal is motor current % .

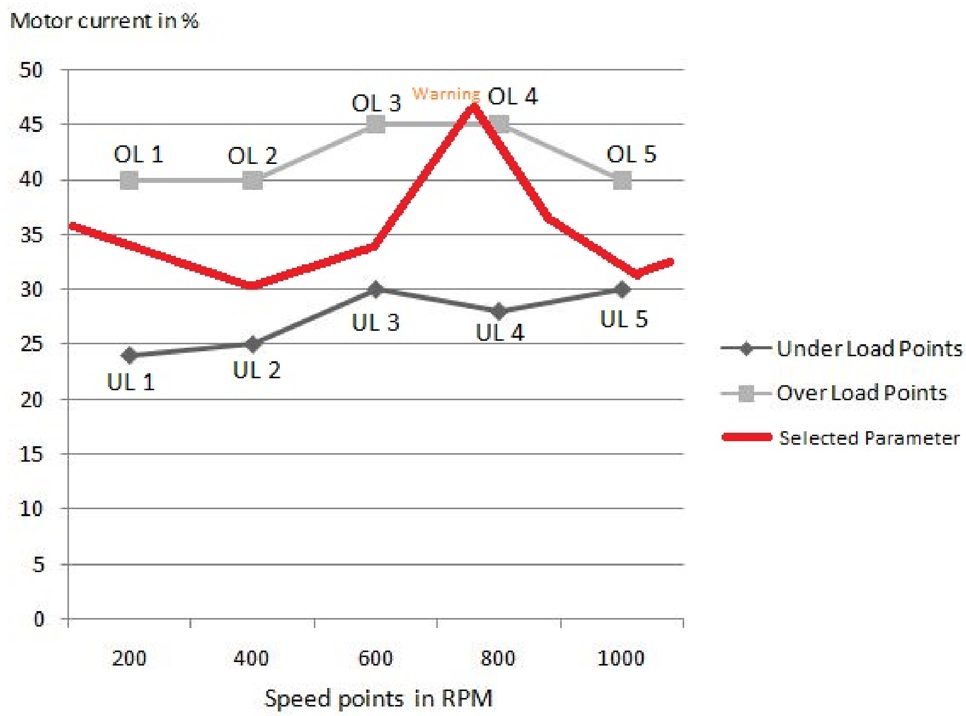

Figure 4.16: User Load Curve with Motor Current % Supervision

Instead of motor current % , user can select Motor speed % , Motor Torque % also. For motor current % with various UL points & OL points, result is carried out as in figure 4.18.

After selecting supervision signal, user can select Warning action, Fault condition & Warning/Fault action if signal exceeds UL points or OL points at corresponding Speed table points.

4.6.2 Applications:

User load curves are useful in below mentioned applications:

- Variable speed applications-Conveyors
- Industrial plants-pumps

4.6.3 Test steps:

User load curve consists following test steps for motor current % testing. After selecting supervision signal tester will define Underload points, Overload points, Warning timers and Speed table points. Tester will set motor speed reference & load after charging the drive. As motor starts with reference speed, if selected supervision signal exceeds Underload limit or Overload limit, corresponding actions such as warning or fault can be taken.

In this testing, selected supervision signal is Motor current %. Applied load type is "Constant load" of 15% - 50% to motor. For Underload limit & Overload limit, "Warning action" has been selected respectively. As warning status goes HIGH, motor current % will be set in such a way, it will return back to operating user curve region by reducing or increasing load.

In motor current % with varying motor speed testing, selected signal is same "motor current %" and load is constant 10% to motor. Here motor speed is varying with 220 RPM - 980 RPM. Underload points are UL1 - UL5 and Overload points are OL1 - OL5.

4.6.4 Test Result: User Load curve with Motor Current %

Test setup used : Emulator system

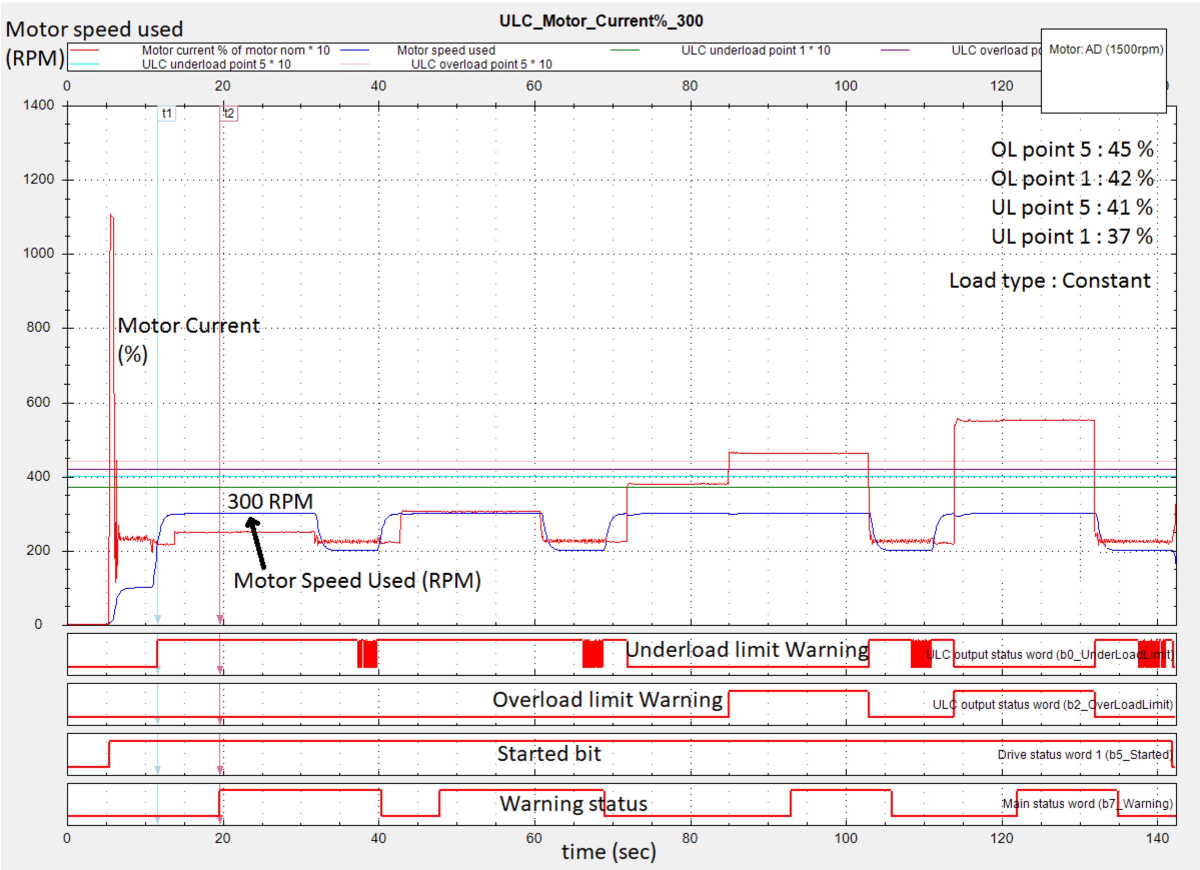

Figure 4.17: MV Drive Automated Testing ULC Motor Current % load

As shown in figure 4.17, it is result of ULC motor current % with change in UL points & OL points. In this testcase, motor current is 23% & Underload point is set to more than 25% so it is showing Underload limit status HIGH. Initially Overload point is set to 60% so motor current % is within range, but as soon as Overload point is set to less than 23% there is overload limit warning in result.

In figure 4.17, Supervision signal is Motor current % & Motor speed reference is 300 RPM. Underload timer is equal to 4 sec which is similar for Overload timer. Hence Active warning bit is going HIGH after delay of 4 sec after User load output status. When drive returns back in defined operation region, active warning bit goes to LOW.

Result: User Load curve with Motor Current % & Different User load points

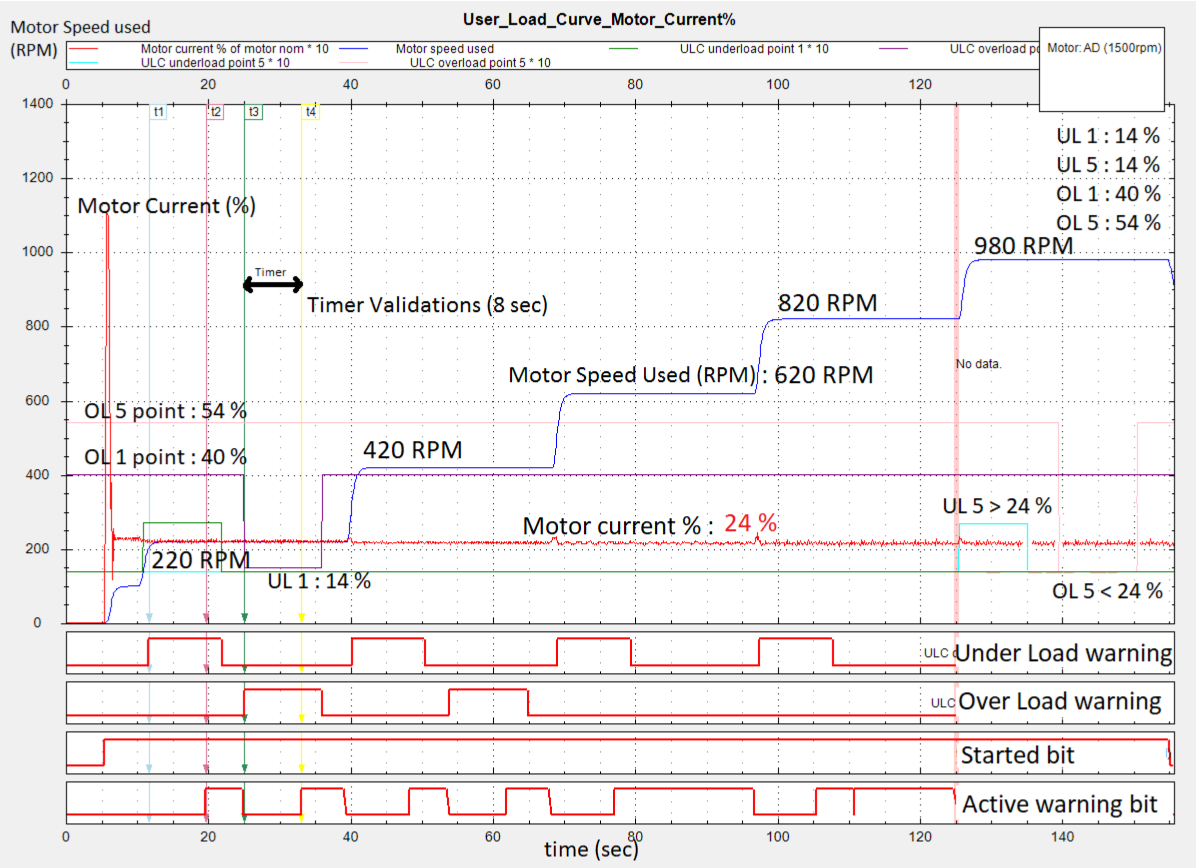

Figure 4.18: MV Drive Automated Testing ULC motor current % in Scalar with various user load points

As shown figure 4.18, it is result of ULC motor current % with various predefined User load points. Here in this testing, Motor speed changes with respect to time & according to it Underload & Overload points also change to verify active warning status. Underload time is 8 second & it is also same for Overload timer.

In above mentioned test result, average motor current(%) is 24% & speed reference changes from 200 RPM to 420 RPM, 620 RPM, 820 RPM & final speed reference is 980 RPM. If motor current(%) is more than defined OL points & less than UL points, active warning bit goes HIGH which is shown in result with "Active Warning bit" status.

4.6.5 Test Validation:

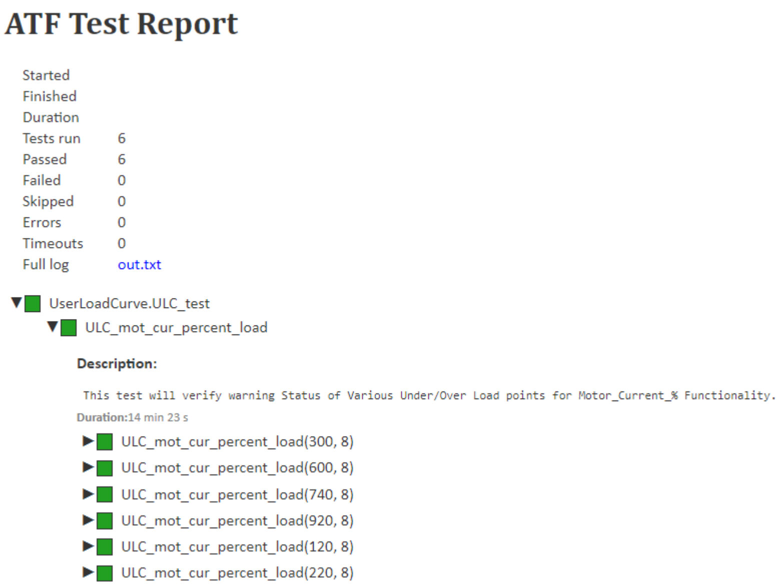

Figure 4.19: ATF test report of ULC motor current % in Scalar

As shown in figure 4.19, it is ATF report of ULC motor current % & with different six combinations testing is carried out. From the report it is visible that test is passing with all asserts in all combinations. In similar way, it is possible to do testing with varying load conditions. In this case motor speed & constant load is varying with respect to time, User load points are fixed.

In above ATF test report speed references are passed as arguments & speed references are 300 RPM, 600 RPM, 740 RPM, 920 RPM, 120 RPM & 220 RPM respectively. User load curve timer is 8 seconds for all combinations.

4.7 Testcase Flux Reference

4.7.1 Description:

In medium voltage drive, user can define & change the source of flux to drive. Most of time motor control is based on Scalar control only so it is required to maintain constant flux value throughout operation. This testing is carried out to verify flux ramp down time & flux ramp up time.

In flux reference testcases, there is direct change in motor stator flux, hence it is possible to change drive parameters such as flux braking and energy optimization.

4.7.2 Test steps:

In flux reference testing, there are three parameters as mentioned below:

- Zero flux reference selection
- User flux reference selection
- Other flux reference selection

In Zero flux reference selection, reference flux value is 0% while in User and Other flux reference selection maximum flux reference limit is 120%.

First, charge the drive and write speed reference. If tester selects "User flux reference selection", user selected flux reference must be provided in %. After starting the drive, check "flux actual %". Make "User flux reference selection" to "Zero flux ref". Calculate flux ramp up time and ramp down time.

In remote scalar control mode, select user flux reference and provide flux reference value as 92%. As motor flux value is directly proportional to output voltage of drive, corresponding changes will occur in output power.

4.7.3 Test Result: Flux reference testing

Test setup used : Emulator system , HiL system

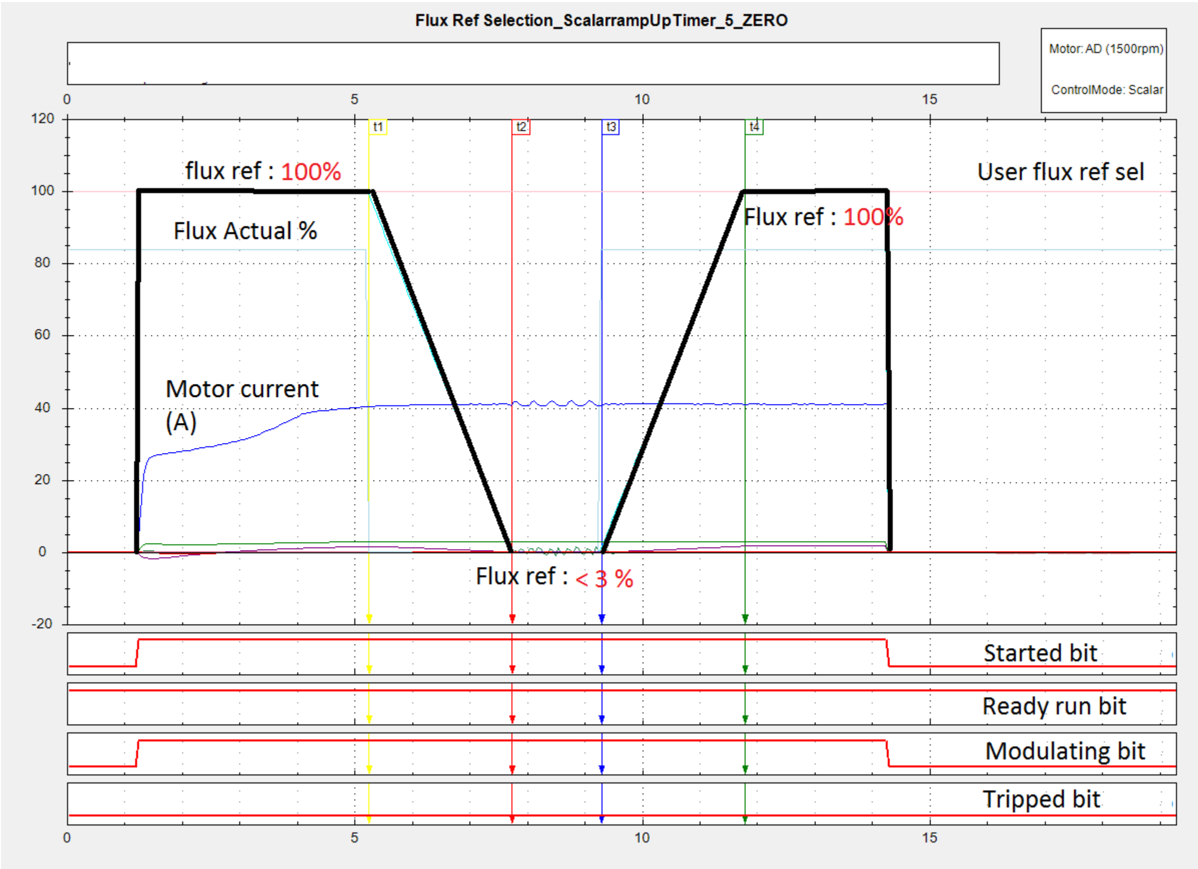

Figure 4.20: MV Drive Automated Testing Flux reference timers in Remote Scalar

In figure 4.20, it is test result of Flux reference selection timer validations. Flux ramp down time & ramp up times are defined as 2.4 seconds. Initially motor speed reference is set to zero RPM & motor is started with flux reference value of 100%. As actual flux reference is set to 0%, from 100% to 0% flux ramp down time is 2.4 seconds.

Similar to Flux ramp down time, as flux reference value is 100% ramp up time is approximately 2.5 seconds. For these defined timings, test is passing with all assertions.

Result: Automated Testing Flux reference with 500 RPM in Remote Scalar

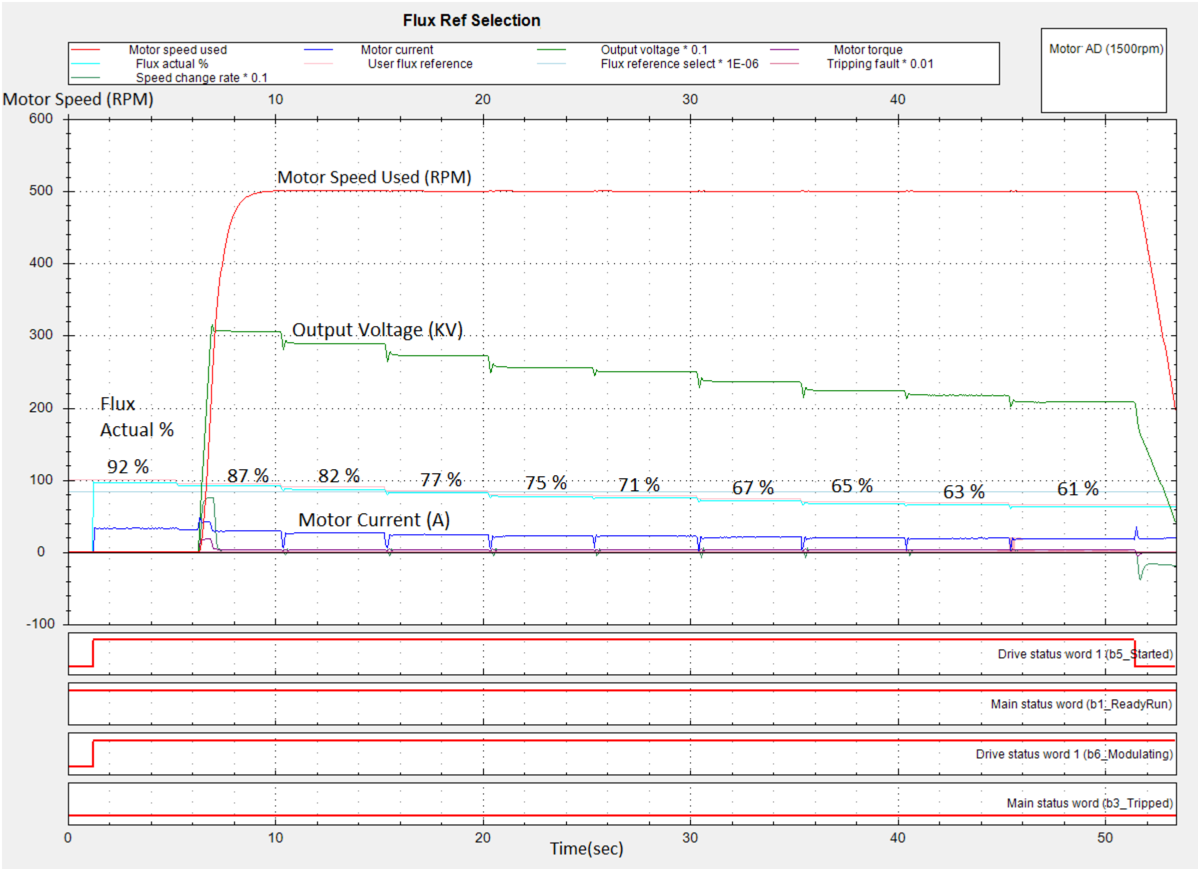

Figure 4.21: MV Drive Automated Testing Flux reference with 500 RPM in Remote Scalar

As shown in above result 4.21, motor speed reference is 500 RPM & initially flux reference value is 100%. Motor speed is constant as 500 RPM. In this test, flux reference is changing from 100% to 90%,80% & so on up to 60%.

With above flux reference testing, corresponding change in output voltage & motor torque has been observed accurately with various speed & flux reference selection.

From the result, it is observable that Motor output voltage is also decreasing as flux reference changes from 100% to 90% & similarly for other user reference selections. There are nominal changes in motor current similar to output voltage of drive.

Chapter 5

Conclusion

In medium voltage drive testing it is necessary to perform "Manual testing" of each drive parameters, while "Automated testing framework" contains more advantages over manual testing. Manual testing is also necessary to perform efficient testing. After performing Automated Testing with framework, it is observed that it saves time, increases efficiency, provide flexibility, improves application software quality by re-usability and saves cost of operation. ATF also provides facility to have proper test report after test completion which is not available in manual testing. With Manual and Automated testing of drive, it is possible to find bugs in software and also to fix it before software release.

In future scope, Automated testing framework can be improved by introducing methods for external control, reusing existing testcases & methods for creation of new testcases and introducing Automated testing framework for HiL system.

Bibliography

[1] Aravind Ingalalli, Nitin Adlok, Shanthibhushan B, Shriram S; ”Automated Testing of Medium Voltage Drive Hardware in Loop Systems”; *IEEE 20th Conference ETFA*, IEEE 2015 page 1-5.

[2] Nitin Adlok, Abhijit Nikam; ”Automatic Testing of Medium Voltage Drive using OPC server Interface”; *2017 International Conference on Smart grids, Power and Advanced Control Engineering (ICSPACE)*, 2017 IEEE.

[3] Claus Klammer, Rudolf Ramler; ”A Journey from Manual Testing to Automated Test Generation in an Industry Project”, *2017 IEEE International Conference on Software Quality, Reliability and Security*, 2017 IEEE.

[4] Dr. Sangeetha Yalamanchili, K.Sitha kumari; ”Comparison of manual and automatic testing using Genetic algorithm for information handling system”; *International conference on Signal Processing, Communication, Power and Embedded System (SCOPES)-2016*, 2016 IEEE.

[5] Saleh Ziaeinejad; Ali Mehrizi-Sani; ”Software-based hardware-in-the-loop real-time simulation of distribution systems”; *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016 IEEE.

[6] Mikhail Mudrov; Anatoliy Ziuzev; Konstantin Nesterov; Stanimir Valtchev; "Power electrical drive Power-Hardware-in-the-Loop system" : *2018 X International Conference on Electrical Power Drive Systems (ICEPDS)*; 2018 IEEE.

[7] Michal Kaczmarek; Przemysaw Koralewicz; "Hardware in the loop simulations of industrial application using system on the chip architecture"; *2016 International Conference on Signals and Electronic Systems (ICSES)*; 2016 IEEE.

[8] Subrina Sultana Noureen; Vishwajit Roy; Stephen B. Bayne; "An overall study of a real-time simulator and application of RT-LAB using MATLAB simpowersystems"; *2017 IEEE Green Energy and Smart Systems Conference (IGESSC)*; 2017 IEEE.

[9] Bin Wang, Chunhua Zhu, Jinfang Sheng; "MDA-Based Automated Generation Method of Test Cases and Supporting Framework"; *2010 2nd International Conference on Computer Engineering and Technology*, 2010 IEEE.

[10] Terry Ericsen, Narain Hingorani, Yuri Khersonsky; "PEBB - POWER ELECTRONICS BUILDING BLOCKS FROM CONCEPT TO REALITY"; *2006 Record of Conference Papers - IEEE Industry Applications Society 53rd Annual Petroleum and Chemical Industry Conference*, 2006 IEEE.

[11] P. K. Steimer, H. E. Gruning, J. Werninger, E. Carroll, S. Klaka, S. Linder; "IGCT - a New Emerging Technology for High Power, Low Cost Inverters"; *IAS '97. Conference Record of the 1997 IEEE Industry Applications Conference Thirty-Second IAS Annual Meeting*, 1997 IEEE.

[12] Drazen Dujic ; Jonas Wahlstroem ; Juan Alberto Marrero Sosa ; Dominik Fritz; "Modular medium voltage drive for demanding applications"; *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*; IEEE 2014.

[13] Dogan Fennibay, Arda Yurdakul, Alper Sen; ”Introducing Hardware-in-Loop Concept to the Hardware/Software Co-design of Real-time Embedded Systems”; *2010 10th IEEE International Conference on Computer and Information Technology*, 2010 IEEE.

[14] Delta electronics Medium Voltage drive product manuals; ”http://www.deltaelectronicsindia.com/Products/MVD.html”

[15] Delta Medium Voltage drive 1000 sereis drive manual; ”https://www.deltaww.com/Products/CategoryListT1.aspx?CID=060103&PID=319&hl=en-US&Name=MVD1000+Series”

[16] ABB Manuals for modular-induction-motors; ”https://new.abb.com/motors-generators/high-voltage-induction-motors/modular-induction-motors”

[17] ABB Manuals for Drives Applications; ”https://library.e.abb.com/public”

[18] ABB Medium Voltage Drive Product manuals; ”https://library.e.abb.com/public/MVD-PHPF01U-EN-REVE.pdf”

[19] ABB Software tools Papers; ”https://new.abb.com/drives/software-tools/drivemonitor”

[20] Simon Abourida ; Christian Dufour ; Jean Belanger ; Takashi Yamada ; Tomoyuki Arasawa ; ”Hardware-In-the-Loop Simulation of Finite-Element Based Motor Drives with RT-LAB and JMAG” ; *2006 IEEE International Symposium on Industrial Electronics*; 2006 IEEE.

[21] M. Bechar ; A. Hazzab ; M. Habbab ; "Real-Time scalar control of induction motor using rt-lab software" ; *2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B)* ; 2017 IEEE.

[22] Zheng Fei ; Zhang Xiao Lin ; Zhang Junjun ; Huang Jingsheng ; "Hardware-in-the-loop simulation, modeling and close-loop testing for three-level photovoltaic grid-connected inverter based on RT-LAB" ; *2014 International Conference on Power System Technology* ; 2014 IEEE.

[23] M. Oettmeier ; R. Bartelt ; C. Heising ; V. Staudt ; A. Steimel ; St. Tietmeyer ; B. Bock ; Ch. Doerlemann ; "Machine emulator: Power-electronics based test equipment for testing high-power drive converters" ; *2010 12th International Conference on Optimization of Electrical and Electronic Equipment* ; 2010 IEEE.

[24] Norbert Grass ; Sebastian Rehmet ; "Full scale power quality emulation system for testing of low voltage grid components" ; *2014 IEEE International Energy Conference (ENERGYCON)* ; 2014 IEEE.

[25] ABB Low Voltage Drive Product manuals; https://library.e.abb.com/public/9ea1314ce99f48b6b626a2529b0a4f91/EN_ACS880_Winch_Ctrl_Prg-_FW_C_A4.pdf