CHAPTER 4

HARDWARE DEVELOPMENT OF STATCOM

4.1 LABORATORY SETUP OF STATCOM

The laboratory setup of the STATCOM consists of the following hardware components:

- Three phase auto transformer used as a 3 phase AC source.
- Three phase inductance represents transmission line.
- Three phase resistance and inductance represent series RL load.
- Three phase inductance parallel with ‘L’ load to give load disturbance.
- Digital signal processor, TMS 320F2407 for generating sine-triangular PWM.
- Personal computer consists of dSPACE and MATLAB software.
- Power quality analyzer made by Krykard company is used to measure real power, reactive power, voltage, frequency and power factor.
- Fluke scope to capture the pulse width modulated output.
- One IPM consists of VSC, capacitor and protection circuits.
- Shunt transformer and capacitor as filter
- Three 3 phase switches, one for connecting STATCOM, one for connecting load and final one for giving load disturbance.
- A CMOS IC 4017 is used as a polling switch.
- dSPACE DS1104 connector panel consisting of 8ADCs and 8DACs and I/O pins to interface with the STATCOM control.

The hardware setup of the STATCOM with ±1kVAR, 75V rating is constructed in the laboratory. Figure 4.1 shows the hardware setup of the STATCOM.

![Figure 4.1 Laboratory setup of STATCOM](image-url)
4.1.1 Three Phase Auto Transformer

A three phase auto transformer with rating 400V/0-470V, 15A is used for varying the bus voltage. It is used as sending end AC source for the bus. Normally, it is maintained at phase to ground voltage of 75Volts.

4.1.2 Three phase transmission line

A three phase transmission line is realized by series inductance winding. Its rating is 72mH. Seven tapings rated at 12mH, 24mH, 26mH, 60mH, 84mH, 108mH, 120mH are present in the inductance winding. Each phase has two inductance winding. One is at sending end and another one is at receiving end side. The resistance of the inductance is $10\, \Omega$. According to the transmission line length, the tapings have been changed. The STATCOM is connected at the middle of the transmission line. In this prototype hardware, the STATCOM is tested by connecting them in the sending end side as well as in the receiving end side separately. But it is not performing well. Finally, it is decided to put the STATCOM at the middle of the transmission line.

4.1.3 Three Phase Series RL Load

A series rheostat of $50\, \Omega/5A$ along with inductance 60mH is used as ‘RL’ series load. To provide a load disturbance, another inductance of 24mH is connected in parallel to the ‘L’ winding of the ‘RL’ load through a switch. This switch is operated to introduce a disturbance.

4.2 DIGITAL SIGNAL PROCESSOR (TMS320F2407A)

A DSP TMS320F2407A is used to generate the SPWM. Six PWMs have been isolated using opto-isolator circuits and given to the six IGBTs of the VSC. 7th PWM will be generated, when over current tries to flow through
the VSC. This PWM is given to breaking IGBT present in the VSC, which isolates the VSC from the bus.

4.2.1 **DSP chip TMS320LF2407A**

The TMS320LF2407A DSP contains DSP core processor and useful peripherals integrated onto a single piece of silicon. The TMS320LF2407A combines the powerful CPU with on-chip memory and peripherals. With the DSP core and control-oriented peripherals integrated into a single chip, users can design very compact and close effective digital control systems, and so Texas named this family of chips as Digital Signal controllers (DSC).

4.2.2 **Features of the TMS320LF2407A**

- Up to 40-MIPS operation
- Three power-down modes
- Code-compatible control-optimized DSPs
- JTAG scan-based emulation
- 3.3V and 5V designs.

4.2.3 **TMS320LF2407A DSP CORE**

The heart of the TMS320LF2407A DSP controller is the c2xx DSP core. This core is a 16-bit fixed-point processor, which means that it works with 16-bit binary numbers. The c2xx core has its own native instruction set of assembly mnemonics or commands. The user can program either in assembly or ‘C’ language. However, to write compact and to have fast execution of programs, assembly language is commonly used.
The TMS320LF2407A core contains the following units:

- A 32-bit Central Arithmetic Logic Unit (CALU)
- A 32-bit accumulator
- Input and output data-scaling shifters for the CALU
- A 16-bit by 16-bit multiplier
- A product scaling shifter
- Eight Auxiliary Registers (ARO – AR7)
- An Auxiliary Register Arithmetic Unit (ARAU)

### 4.2.4 Central Arithmetic Logic Unit (CALU)

The DSP core performs 2’s-complement arithmetic using the 32-bit CALU. The CALU uses 16-bit words taken from the data memory, derived from an immediate instruction, or from the 32-bit multiplier results. In addition to arithmetic operation, the CALU can perform Boolean operation.

### 4.2.5 Embedded Peripherals

The brain of the TMS320LF2407A DSP is the c2xx core. It contains several control-oriented peripherals on-chip. The peripherals of the LF2407A make virtually any digital control requirement possible. Their application ranges from Analog to Digital Conversion (ADC) and PWM generation. Communication peripherals make possible the communication with external peripheral, personal computers, or other DSP processor. The embedded peripherals inside the LF2407A are listed below.

- Two event managers A and B
- General Purpose (GP) timers
- Analog-To-Digital Converter
- Controller Area Network (CAN) interface
4.2.6 Sine Triangular PWM Generation using DSP TMS320F2407

A sine wave of 50 Hz is compared with a carrier wave of 20 kHz and accordingly the pulses are generated. The carrier wave is a triangular wave. The maximum magnitude of both waves is 5 Volts. The pulse width at the edges of the sine wave is higher than at the middle of the sine wave. In order to generate a sine wave, a look up table is used in DSP TMS320F2407. To produce triangular wave, a timer register is used in the same DSP. The concept of sine triangular PWM is as shown in Figure 4.2.

Figure 4.2 Sine triangular PWM generation
where $V_t$, $V_s$, $V_m$ and $V_p$ are the triangular, sine, maximum and pulse voltage magnitudes respectively.

### 4.2.7 Modulation index

The modulation index ($K$) is defined by the following equation

$$K = \frac{\text{magnitude of the modulating signal}}{\text{magnitude of the carrier signal}}$$

Here, the modulating signal is the sine wave. The carrier wave is a triangular wave of 20 KHz.

### 4.2.8 Phase angle or firing angle

It is an angle between the converter output voltage and the 3 phase bus voltage. It is measured in degree. The maximum value of firing angle is limited from $-25^\circ$ to $+25^\circ$ for safer operation.

### 4.3 PERSONAL COMPUTER WITH dSPACE SOFTWARE

Personal computer consists of 256MB ROM, Intel Pentium IV processor (2.4 GHz) and Intel original mother board. dPSACE software which is installed in this PC consists of DS1104 DSP board. By using this dSPACE software, the instantaneous wave forms can be visualized using plotter instrument.

The dSPACE software belongs to Germany company. It has the following features

- Hardware and software platforms are based on MATLAB/ Simulink
- Integrated environment.
• Reliability, scalability and accuracy
• The Kits are real-time development systems with easy-to-use real-time hardware.
• Include software for automatic implementation of MATLAB /Simulink models on dSPACE hardware
• Automatic code generation
• Graphically supported I/O configuration
• Demonstrates high-end control development - from block diagram design to online controller optimization.
• Tests even the most complex control systems in real time.
• More comprehensive and more systematic tests in shorter time
• Works under easy-to-use and intuitive windows interface.
• Implements simulink models on dSPACE real-time hardware within seconds
• Observes the effects of parameter changes on system’s behavior

The DS1104 consists of the following components:
• Power PC 603e running at 250 MHz
• Slave DSP TMS320F240 8MB boot flash, 32MB SDRAM
• 8 A/D and 8 D/A
• 20 Digital I/O
• Incremental Encoder Interface
• Serial Interface( UART)
• Sits on PCI slot in a PC
The architecture of the DS1104 board is shown in Figure 4.3

4.3.1 MATLAB-dSPACE interface

In dSPACE environment, the MATLAB will act as a back end tool. dSPACE is acting as a front end tool. The MATLAB-dSPACE diagram is shown in Figure 4.4.
In MATLAB environment, the simulink model for the control system along with the real time workshop blocks such as digital I/O, ADCs and DACs blocks are present.

In dSPACE environment, the control desk consists of tools such as knob, plotter, and display blocks.

In order to generate the DSP code from the simulink model, a ‘C’ compiler is present. In real time interface, the DS1104 board makes the interface between the MATLAB and dSPACE.

It is possible to implement the simulink model of any system on dSPACE real time hardware within seconds and to observe the effects of parameter changes on system’s behavior. This software helps in varying the system parameters while doing the simulation and there by the dynamic performance of the system can easily be observed.

The dSPACE layout of STATCOM model can be created in SIMULINK environment. Then, this model layout is converted into DSP code which runs in the in-built TMS320F240 DSP processor in the dSPACE.
controller. A dSPACE Connector panel CLP1104 ports provide easy access to all input and output signals of the DS1104 board.

4.4 POWER QUALITY ANALYZER

By using the Krykard make power quality analyzer, the value of real power and reactive power flowing through the line can be measured. Power factor, frequency, harmonics up to 49th order and THD can also be measured using this analyzer.

4.5 FLUKE SCOPE TO CAPTURE THE SPWM

By using the fluke power quality analyzer (200MHz), the signals of high frequency even in the order of 200MHz can be visualized. Here, it is used to capture the SPWM generated from the DSP TMS320F2407A.

4.6 IPM AND ITS COMPONENTS

IPMs are advanced hybrid power devices that combine high-speed, low loss IGBTs with optimized gate drive and protection circuitry. Highly effective over-current and short-circuit protection are realized through the use of advanced current sense IGBT chips that allow continuous monitoring of power device current.

A Mitsubishi make IGBT module is used as VSC. It consists of seven IGBTs. IGBTs are anti-parallel with diodes. Six IGBTs for converter operation and one IGBT for protecting the VSC from over current. Heat sinks have been mounted on the module for dissipating the heat.

SPWMs are generated and they are used to provide gating pulses for the VSC. In a VSC, the DC capacitor voltage always has one polarity, while the power reversal is achieved by reversal of DC current and, therefore
the VSC requires only unidirectional voltage blocking. The IGBT can be used in low and medium power applications going up to a few tens of megawatts. The advantages of this semiconductor device are:

- Its fast turn-on and turn-off capabilities
- Can be used in PWM converters operating at high frequency.
- It has low switching losses and good current limiting capability.
- It also overcomes the limitations of the GTO regarding its drive power, snubber circuits, and dv/dt limitations.

The switches should be designed only for forward blocking voltage, as the diodes ensure that the voltage polarity of each switch is unidirectional. The current is assumed positive, if it flows from the ac to the dc side (a rectifier operation); the current is assumed to be negative, when it flows from the DC to the AC side (an inverter operation). The circuit diagram of IPM is shown in Figure 4.5.

![Figure 4.5 Circuit diagram of IPM](image-url)
It consists of switches $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, $S_6$ and $S_B$. Each switch consists of an IGBT and anti paralled diode. $S_B$ is the breaking IGBT which is used to protect the six IGBT bridge, when fault current comes.

### 4.6.1 Operation of IPM

The IPM consists of 6 IGBTs whose gate pulses are given from DSP TMS320LF2407. The supply is given separately to this module. The firing pulses are controlled by PWM thereby the output voltage of the inverter consists of six IGBT’s, can be controlled with respect to the requirement. If the current or voltage limits exceed the threshold level, the protection circuitry will protect the equipments.

### 4.6.2 Functional circuitry of IPM (single unit of IGBT)

The IPM has totally 7 IGBTs. A single unit of IGBT in IPM is shown in Figure 4.6

![Figure 4.6 Functional circuitry of single unit of the IPM](image)

It consists of the following components

- Current sense IGBT
- Temperature sensor
- Gate control circuit
- Gate drive circuit
- Over temperature sensor
- Under voltage (UV) lock outs
- Over current and short circuit protection
- Isolated power supply
- Two numbers of isolating interface circuits

Current sense IGBT has two emitters. One is for output and other one is to sense the current output. This current output, is given to gate control circuits, which is used for over current and short circuit protection.

Temperature sensor senses the temperature of the IGBT. This temperature output is given to gate drive circuit which is used for over temperature protection.

One isolated power supply is available for the PWM and gate control circuits. It gives the power to the opto isolator and other isolating devices.

The isolating interfacing circuit consists of 7 opto isolators. 7 PWM signals are isolated in order to avoid the short circuit and are given to the base of IGBTs.

When over current occurs, the fault is detected at the gate drive circuit. This signal is detected and one PWM signal is given to the base of braking IGBT, where the remaining IGBTs are isolated from the AC power supply. When short circuit occurs, the 6 PWM pulses have been cut and the bridge is prevented from damage.
4.6.3 Advantages of IPM

The advantages of the IPM are listed below

- Improvement in system performance and reliability over conventional IGBTs.
- Design and development effort is simplified.
- Increased system reliability through automated IPM assembly and test, and reduction in the number of components that must be purchased, stored, and assembled.
- Low switching losses.
- All IPMs use the same standardized gate control interface with logic level control circuits allowing extension of the product line without additional drive circuit design.
- The ability of the IPM to self protect in fault situations reduces the chance of device destruction during development testing as well as in field stress situations.

4.7 SHUNT TRANSFORMER AND CAPACITOR AS FILTER

A 3 phase shunt transformer, which has the rating of 400V/400V, 6kVA is connected with the 3 phase capacitors with the rating of 12.5µF, 400V to filter out the 20 kHz content.

4.8 CMOS SWITCH FOR SWITCHING THE POLLING SWITCHES

Three polling terminals from the DSP kit are available outside the kit. First one is for selecting ‘K’ or ‘α’. The second one is for incrementing the values of ‘K’ or ‘α’. The third one is for decrementing the values of ‘K’ or
‘α’. The signal from the dSPACE software controls these switches. Figure 4.7 shows the pin diagram of CMOS switch 4016.

![Figure 4.7 Pin diagram of IC4016](image)

When ‘E’ is LOW, the switch is open. The switch is closed, when ‘E’ is HIGH. This is the basic operation principle of the CMOS switch used in the circuitry. They are used as S1 and S2. These two switches are used to vary the modulation index ‘K’ and firing angle ‘α’. The 4016 contains four switches. Each switch has two input/output terminals, ‘Y’ and ‘Z’ and an enable terminal ‘E’. V<sub>dd</sub> and V<sub>ss</sub> are the energizing pins of CMOS.

4.9 SUMMARY

The real-time hardware setup of the STATCOM consists of various software as well as hardware components. The details of the components present in this hardware setup and their role are discussed in detail in this chapter.