DSP BASED MULTICHANNEL MODULAR SSPC DESIGN FOR SPDU’s

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ABSTRACT

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M.Sc. in Electrical and Electronics Engineering

Supervisor: Prof. Dr. İres İSKENDER
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In this study, a DSP-based, 16 channel, 28V_{DC} solid-state power controller with 238A total current rating was designed to be used in solid-state power distribution unit. Traditional power distribution units used as Secondary Power Distribution Unit (SPDU) in aircraft with relays and circuit breakers and solid-state power distribution units designed with semiconductor switches were compared and detailed design processes and features of new-generation PDUs were explained. It is explained during in the design of the solid-state power controller how, should the power requirement increase in the future, this need may be satisfied with the minimum changes possible and how time and cost savings can be achieved with this design. This SSPC was designed for use on platforms such as military ground and naval vehicles as well as aircraft. Software design one of the key features of SSPC was explained in detail. Software algorithms were developed to protect loads based on I^2T approach. Theoretically designed circuits and software were put into practice and necessary performance evaluations were made.

Keywords: Power Distribution Unit, PDU, Solid State Power Controller, SSPC, SSPDU, Aircraft, Military

ÖZET

İGDB'LER İÇİN DSP TABANLI ÇOK KANALLI KHGDB TASARIMI

ERDOĞDU, DOĞUKAN
Elektrik-Elektronik Mühendisliği Yüksek Lisans

Danışman: Prof. Dr. İres İSKENDER
Şubat 2023, 61 sayfa

Bu çalışmada, katı hal güç dağıtım ünitesinde kullanılmak üzere DSP tabanlı 16 kanal, 238A toplam akım değerine sahip $28V_{DC}$ katı hal güç kontrolcüsü tasarlanmıştır. Uçaklarda İkincil Güç Dağıtım Birimi (İGDB) olarak kullanılan, röle ve devre kesiciler ile tasarlanan geleneksel güç dağıtım birimleri ile yarı iletken anahtarlarla tasarlanan katı hal güç dağıtım üniteleri karşılaştırılmış ve yeni nesil GDB'lerin detaylı tasarım süreçleri ve özellikleri anlatılmıştır. Katı hal güç kontrolcüsü tasarımında, gelecekte güç ihtiyacının artması durumunda bu ihtiyacın mümkün olan en az değişikliklerle nasıl karşılanabileceği ve bu tasarım ile nasıl zaman ve maliyet tasarrufu sağlanabileceği anlatılmaktadır. Bu GDB, hava araçlarının yanı sıra, askeri kara ve deniz araçları gibi platformlarda kullanılmak üzere tasarlanmıştır. GDB'nin temel özelliklerinden biri olan yazılım tasarımı ayrıntılı olarak açıklanmıştır. Yükleri korumak için I^2T gibi yazılım algoritmaları geliştirilmiştir. Teorik olarak tasarlanan devreler ve yazılımlar uygulamaya alınmış ve gerekli performans değerlendirmeleri yapılmıştır.

Keywords: Güç Dağıtım Birimi, GDB, İGDB, Katı Hal Güç Kontrolcüsü, Hava Aracı, Askeri

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

V_{DC}	: Volts of Direct Current
V_{AC}	: Volts of Alternative Current
A	: Ampere
W	: Watt
Ω	: Ohm
°C	: Celsius
µ	: micro
Hz	: Hertz
ms	: millisecond
mm	: millimeter
$R_{DS(ON)}$	: Drain-source on-state resistance
V_{DS}	: Drain-source voltage
R_{sns}	: Sense Resistance

Abbreviations

CH	: Channel
SSPC	: Solid State Power Controller
SSPDU	: Solid State Power Distribution Unit
PDU	: Power Distribution Unit
EEPROM	: Electronically Erasable Programmable Read-Only Memory
PCB	: Printed Circuit Board
MOSFET	: Metal–oxide–semiconductor field-effect transistor
I^2C	: Inter-Integrated Circuit
SPI	: Serial Peripheral Interface
ADC	: Analog to Digital Converter
DSP	: Digital Signal Processor
GUI	: Graphical User Interface

Si	: Silicone
ENIG	: Electroless Nickel Immersion Gold
ENEPIG	: Electroless Nickel Electroless Palladium Immersion Gold
ETX	: End of Text
STX	: Start of Text
ASCII	: American Standard Code for Information Interchange
MSB	: Most Significant Byte
LRC	: Longitudinal Redundancy Check
MEA	: More Electric Aircraft
AEA	: All Electric Aircraft
APU	: Auxiliary Power Unit
MFD	: Multi-Functional Display

CHAPTER I
INTRODUCTION

1.1 Background

The design of the power distribution system in modern ground, naval and aviation platforms bring many challenges. Expectations such as the increase in power needed over time, the demands for improved reliability, the need to reduce weight and volume, and the ability of power distribution systems to detect and take precautions more specifically necessitate more competitive product designs. This transformation, which emerged especially under the leadership of the aviation industry, started to be called Solid State Power Controllers of new generation power distribution units.

The idea of more electrical aircraft (MEA) and all electric aircraft (AEA) is becoming a reality due to the rapid development of electrical and electronic technologies. Some of the most recent MEA systems have begun using electricity to power aircraft subsystems that were previously powered by pneumatic, hydraulic, or mechanical means, such as flight control actuators, environmental control systems (ECS), ice protection systems (IPS), and many more [1]. The power distribution systems utilized in aircraft are evolving along with these new ideas. The research society and system architects have shown interest in intelligent power distribution systems and automatic load management as methods to most effectively and efficiently use the available electrical power. Due to the intricate nature of the interface between system power and conversion systems, SSPC is one of the major components in this type of architecture that necessitates a significant amount of attention to detail while designing [1].

1.2 Objectives of Thesis

The main purpose of this thesis is to design a new generation solid-state power distribution unit within the framework of transition from electromechanical switching elements and circuit breakers to solid-state switches. In this context, DSP-based 16-

channel, $28V_{DC}$ solid-state power controller with 238A total current rating was designed. The operating voltage of the SSPC, which is intended for widespread use on various platforms including aviation, naval, and ground systems, has been selected at $28V_{DC}$.

1.3 Thesis Outline

The main goal of this thesis is to design and implement a solid-state power controller with $28V_{DC}$,16 Channel, 238A total current rating capacity. The key points of the designed solid-state power controller are that SSPC can be used in a modular structure, that it can operate without the need for any active cooling, and that it provides ease of use and flexibility to the user in line with the features of the developed software.

In Chapter 2, conventional power distribution units and new-generation solid-state power distribution are given and comparisons are made with respect to each other.

In Chapter 3, the hardware design of a solid-state power distribution unit is explained. After a block diagram is given, the main parts that make up the SSPC are detailed.

In Chapter 4, the software design of a solid-state power distribution unit is explained. Software features developed for users and software protection algorithms such as I^2T are discussed.

In Chapter 5, with the aid of recorded data and graphics, test results for a solid-state power distribution unit are presented and thoroughly reviewed.

In Chapter 6, The results of solid-state power distribution unit design and implementation are presented. In addition, information about some of the studies planned to be carried out in the future is given.

1.4 Traditional Aircraft Power System

The architecture of an aircraft electrical network typically consists of divisions for generation, conversion, distribution, and protection. Depending on the type, aircraft usually produces output voltage of $115V_{ac}$ and 400 Hz power [2]. This generated power is converted to $270V_{DC}$ with a transformer rectifier unit [2]. Then, in addition to this DC voltage, it is reduced to $28V_{DC}$ using a with DC/DC converters. In addition, the $28V_{DC}$ voltage to be used for distribution can be provided by one or more batteries. [2] A simplified Aircraft Electrical System is shown in Figure 1.

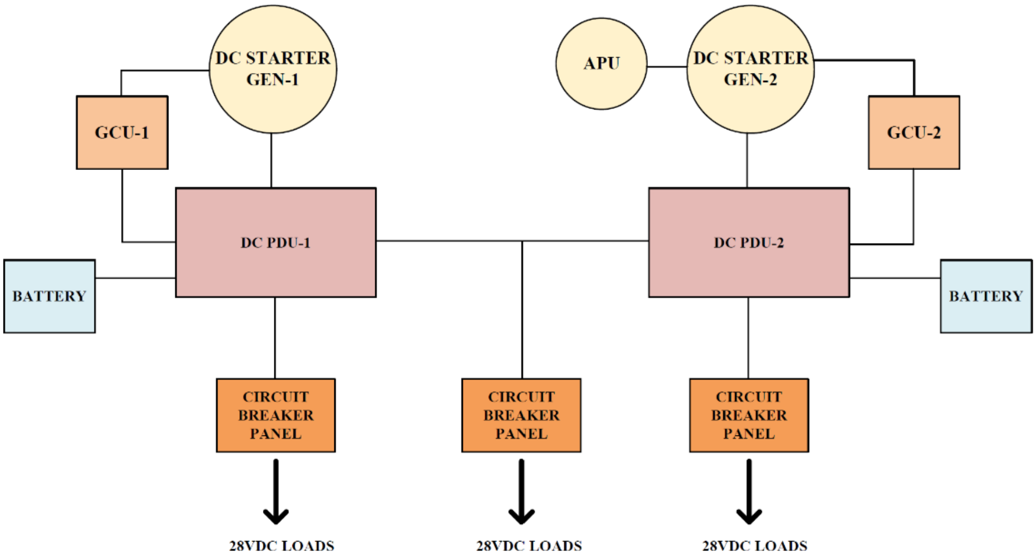

Figure 1: Simplified Traditional Aircraft Electrical System

1.5 System Overview of Traditional PDU

Figure 2 illustrates the circuit breaker block, control panel, relay/contactor block, and harness as the four main components of conventional power distribution units. Power distribution systems in aircraft may vary depending on the type of aircraft and the number of engines. This also affects the locations within the aircraft where the power distribution systems are located. PDU control panels are usually located in the cockpit for easy pilot access. As the PDU is in a central location, as shown in Figure 3, the power cables are connected to the circuit breakers from the DC bus first, then connected to the loads they are supposed to feed, and then switched with relays or contactors. Since there is power transmission over the harness made here, the cable diameters increase according to the current requirement. When it is desired to switch relays or contactors separately, a separate control connection must be established. The cable diameters used for control signals are relatively smaller than the cables used for power circuit breakers.

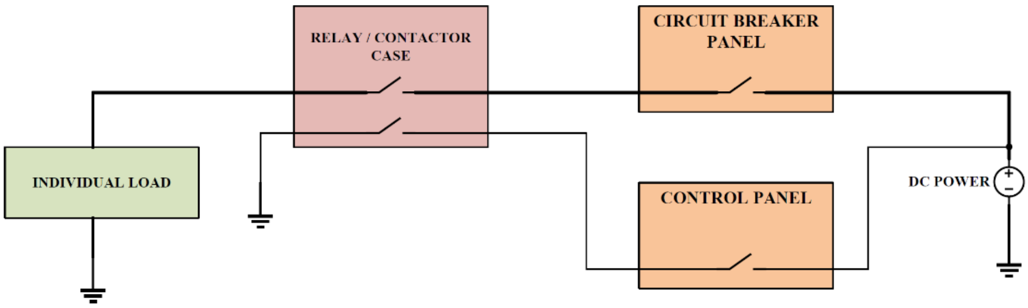

Figure 2: Traditional Power Distribution Block

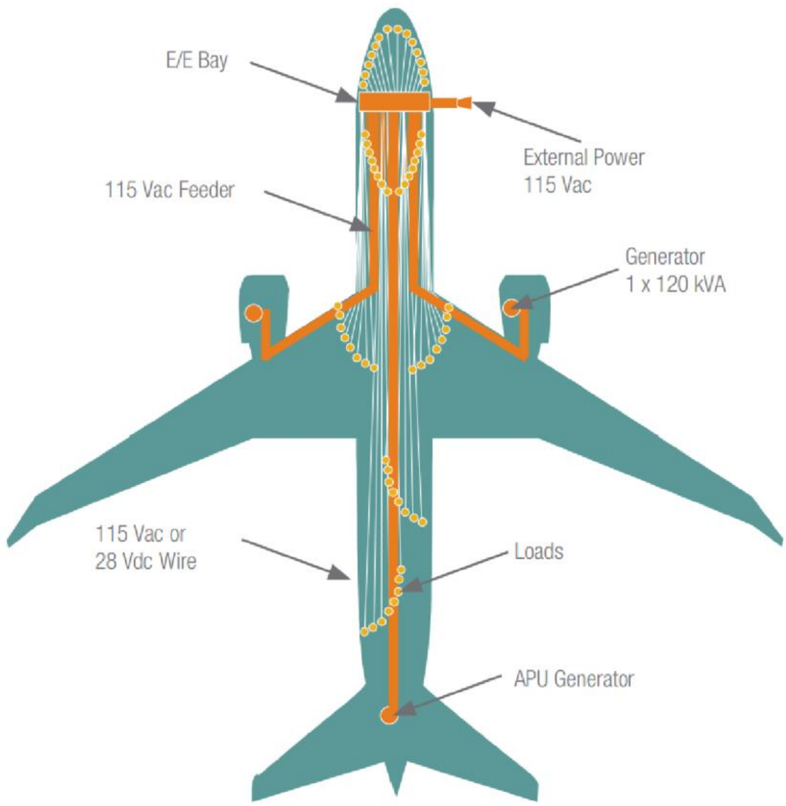

Figure 3: Traditional Aircraft with centralized PDU [3]

1.6 System Overview of SSPDU

Solid-state power distribution units may consist of one or more SSPCs. Circuit breaker block and contactor blocks placed in conventional power distribution systems are combined in new-generation solid-state power distribution units. Therefore, there are required for the harness to be extended between the contactors and circuit breakers. SSPDUs has 3 main connection interfaces. Firstly, there is a communication line where the user queries the loads and inquiries about the status information of the loads. Another connection interface is the input of the power to be distributed to via SSPDU.

The last main connections are the power connections between the loads to be fed and the SSPDU. Figure 4 shows the general structure of solid-state power distribution units.

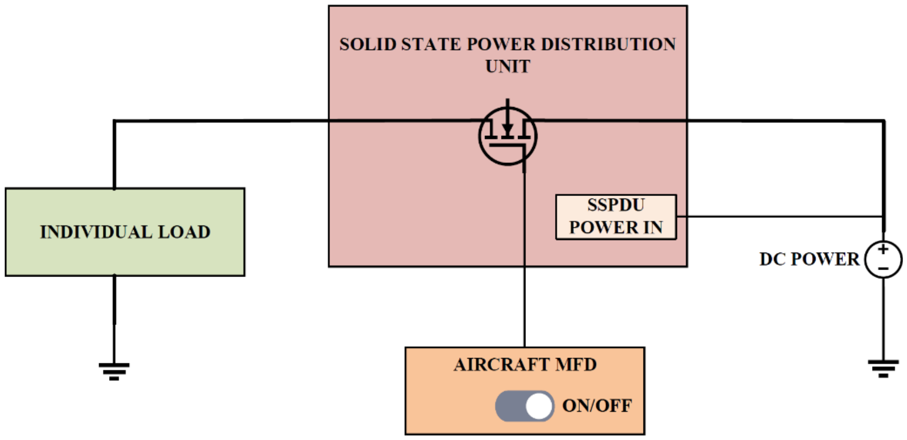

Figure 4: MEA with Solid State Power Distribution System [3]

SSPCs provide remote control via communication interfaces. For this reason, instead of a single power distribution unit at the center, multiple SSPCs can be used close to load groups at different locations on the aircraft. As shown in Figure 5, major loads are located in different areas of the aircraft. According to this distribution, SSPCs are positioned locally.

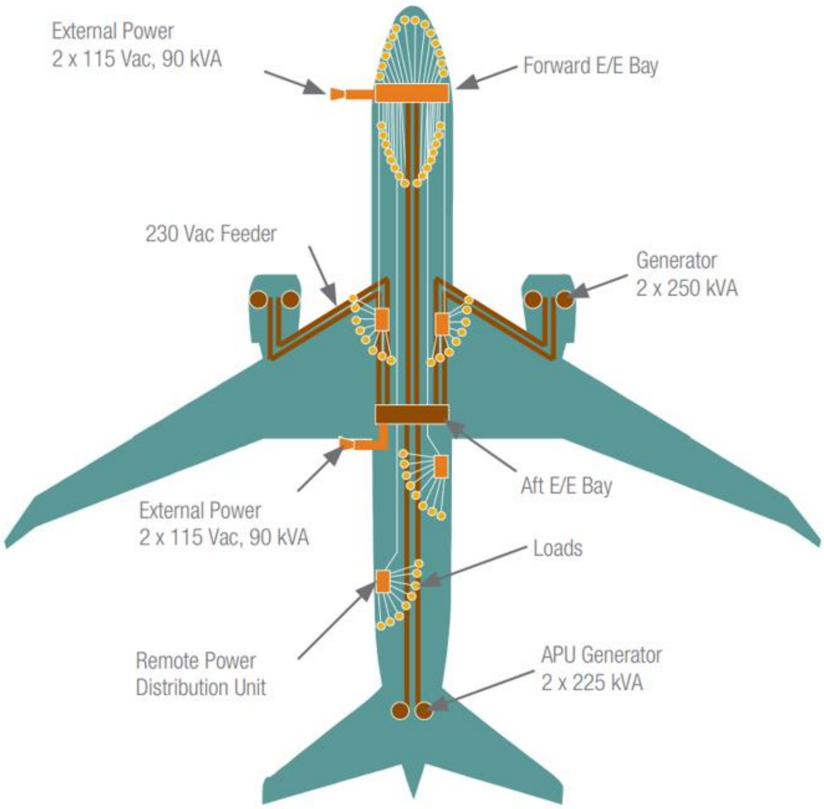

Figure 5: Solid-State Power Distribution Block

CHAPTER II

COMPARISON OF SSPDU VS TRADITIONAL PDU

In conventional power distribution systems, switching of loads is done with electromechanical relays used in conjunction with the circuit breaker [3]. The electromechanical relay structure is given in Figure 6 [3].

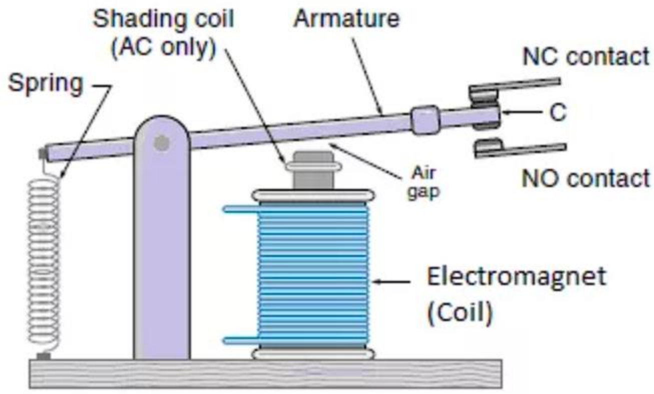

Figure 6: Electromechanical Relay [4]

In the structure of the relay, there is a coil on the magnetic core. When a voltage is applied the coil is energized and produces an electromagnetic field. The armature, which is a moving part, contacts other contacts. Thus, the relay turns on. When the energy supplied to the relay coil is cut off, the armature is in its normal position since there is no magnetic flux.

Electromechanical relays have many drawbacks which are large footprint, contact deformation, sensitivity to vibration, arc welding and slow switching [2]. Slow switching is not a problem, as there is no continuous switching at a certain frequency. Compactness and size are taken into account in almost all designs today. Considering that the maximum channel current value is 30A in the design, the size of a PCB-type relay is approximately shown in Figure 7.

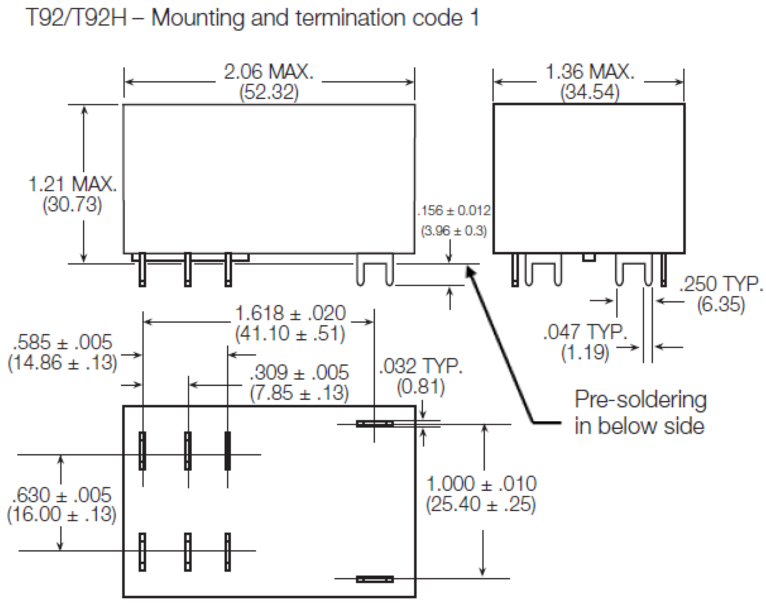

Figure 7: Electromechanical Relay Dimensions [5]

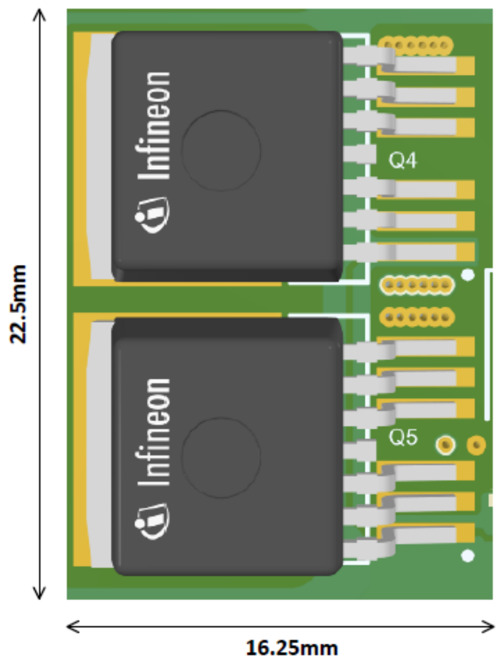

Figure 8: Parallel MOSFET Configuration Dimensions as Load Switch

The relay takes up 52x34mm space on the PCB, excluding the drive circuit. On the other hand, two Si MOSFETs used for one channel in SSPC occupy 22.5 x 16.25mm space. This shows that the MOSFETs used as switches take up almost half the space compared to the electromechanical relay. The main difference is between the heights of the components. The height of relay (30.73 mm) is approximately six times of MOSFET height which is 4.57 mm.

The operational life of the component is another difference between the two switches. MOSFETs have an unlimited cycle life due to their structure. Electromechanical relays have a limited switching cycle during their lifetime. In the relay we compared, this number is 100.000 cycles at a resistive load of 25A.

Another difference between electromechanical relays and semiconductor switches is that relays contain mechanical and moving parts, making them susceptible to vibration and shock. A mis-contact between contacts under vibration or a shock can cause problems. It is not structurally possible to have such a problem in semiconductor switches.

One of the important shortcomings of relays is its power losses. There are two different reasons for the power losses in the relays. The first of these is the loss on the coil and the other is the loss on the contacts. In addition, contact power losses vary depending on the current value and the resistance of the contacts. The losses on the relay are calculated using the equations given below.

$$P_{Loss(CONTACT)} = I_{CH}^2 \times R_{(CONTACT)} \tag{2.1}$$

$$P_{Loss(COIL)} = V_{(DRIVE)}^2 \ / \ R_{(COIL)} \tag{2.2}$$

$$P_{Loss(TOTAL)} = P_{Loss(COIL)} + P_{Loss(CONTACT)} \tag{2.3}$$

The power loss of a relay depends on its internal resistance and the applied voltage level. For a relay driven with $24V_{DC}$, this power loss at coil is around 1.7W [5]. For the relay we compared the contacts voltage drop is 100 mV. At the maximum channel current of 25A, a loss of 2.5W is occur on the relay. For a channel with a current rating of 25A, the total power loss on the relay is 4.2W. The power loss of circuit breakers used with relays in traditional power distribution systems should also be added to this value. For example, the circuit breaker model used has a contact power loss of 3W [1]. At a current of 25A, the loss that is occur here is calculated thermal breaker loss 5W and thermal element loss is generally 2W [1]. If the losses in the relays and circuit breakers are added up, when a 25A output is wanted to be switched in conventional power distribution systems, a power loss of approximately 14.2W is experienced, excluding transmission losses.

The power losses of MOSFET, sense resistor and the total power losses can be calculated from the following equations.

$$P_{Loss(sense)} = I_{CH}^2 \times R_{(sense)} \tag{2.4}$$

$$P_{Loss(MOSFET)} = I_{CH}^2 \times R_{DS(ON)} \tag{2.5}$$

$$P_{Loss(TOTAL)} = P_{Loss(sense)} + P_{Loss(MOSFET)} \tag{2.6}$$

The conduction loss of a MOSFET depends on $R_{DS(ON)}$ and its current. The most important factor is the value of $R_{DS(ON)}$ of the MOSFET. The $R_{DS(ON)}$ values of MOSFETs are different. It is possible to find MOSFET's with a wide variety of $R_{DS(ON)}$ values. While trying to find the MOSFET with minimum $R_{DS(ON)}$ resistance, footprint and V_{DS} value should also be taken into account, specific to the application. Footprint is directly related to the PCB placement, heat dissipation and V_{DS} is related to the switching voltage value. Considering all of these, Infineon IPB036N12N3GATMA1 MOSFET with drain-source voltage of $120V_{DC}$, $R_{DS(ON)}$ resistance of 3.6 mΩ and D^2PAK footprint was selected [9]. For the 25A channel, 300μΩ will be used as the current sense resistor. For SSPC to be operational without the need for any active cooling, two MOSFETs will be used in parallel in the output channels. In this case, 12.5A current will flow through each MOSFET. The total loss will be 1.3125W. As can be seen, the loss in conventional power distribution units is up to 11 times higher at the same current rating.

As mentioned before, circuit breakers are used together with electromechanical relays in order to take protection at the outputs. Circuit breakers are connected to the transmission line in series. This means that the line coming out of the relay, which is the switching element, must first go to the circuit breaker, not directly to the output. This means extra harness for conventional PDUs. The fact that the circuit breakers are located in the boxes where the relays are located or in a different place affects the harness significantly. Since this wiring consists of current-carrying cables, the diameters of the cables are also relatively large. The length of these current-carrying cables creates a serious disadvantage compared to SSPCs in terms of both cost and weight. In Table 1, the comparison of traditional power distribution units and a new generation of solid-state distribution units is given.

Table 1: Traditional PDU And Solid-State PDU Comparison

Features	**Traditional Power Distribution Unit**	**Solid-State Power Distribution Unit**
Size and Dimension		✓
Reduced harness and weight		✓
Efficiency		✓
Less Cooling Need		✓
Lifetime		✓
Labor		✓
Shock & Vibration Sensitivity	✓	
Configurable Output I^2T protection		✓
Configurable Output Current Rating		✓
Output paralleling		✓
Reliability		✓
Working with both AC and DC	✓	

CHAPTER III
DESIGNING SOLID STATE POWER CONTROLLER

3.1 Block Diagram and Overview

The main task of the SSPC is to distribute the incoming $28V_{DC}$ voltage to the outputs in a controlled manner. During this power distribution, necessary protection measures are taken and many different software benefits are provided. As shown in Figure 9, there are different circuit blocks that serve many purposes to perform these operations.

First of all, the DSP as the heart of the SSPC can be mentioned. DSP has many functions such as driving outputs, measuring voltage and current values instantaneously, exchanging data over communication protocols determined with the outside, and storing user profiles on the board. There are internal DC-DC converter circuit blocks on the board so that both the DSP and the circuits on the board can work without the need for an external source. The nominal distribution voltage of SSPC is $28V_{DC}$, but it can be operational between $9\text{-}36V_{DC}$ input source thanks to these converter circuits. There is an I^2C line controlled by DSP on the board. Through this line, instant temperature monitoring and protection can be done with the temperature sensor located in three different regions of the board. User profiles are stored internally on the card with the EEPROM block connected to the same I^2C line. Thus, in case of power failure, saved user profiles can be activated. It communicates with the ADC on the card via SPI, which is another serial communication protocol to be used in the card. With this ADC, the voltage values in the output channels are measured instantly. There are CAN-BUS and RS485 circuit blocks to be able to execute the commands sent by the user through software and to send instant information to the user. There is a separate circuit block where this communication can be hardware based via discrete signals.

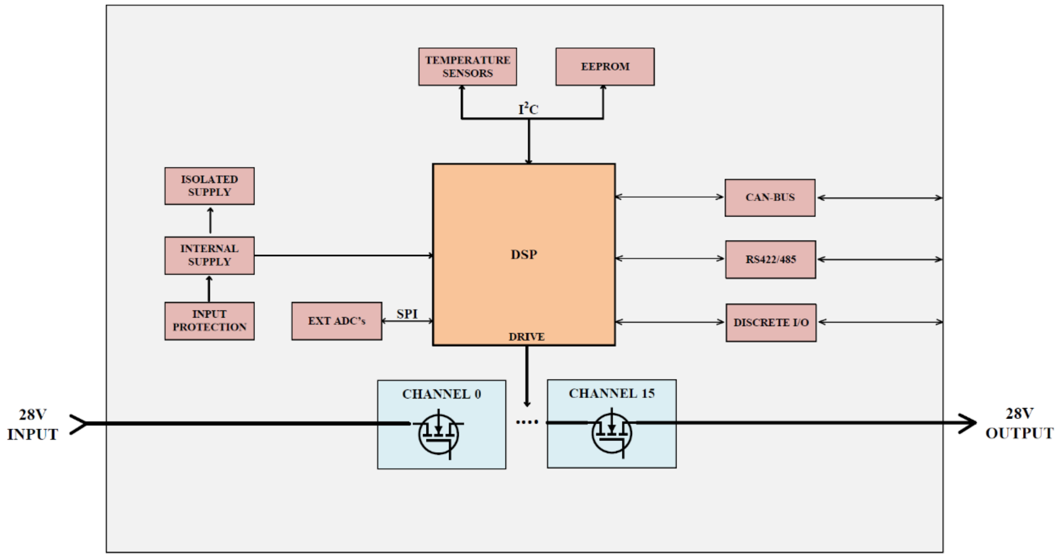

Figure 9: SSPC Block Diagram

3.2 Switching Circuit

The main circuit block in SSPC is the output switching circuit as shown in Figure 10. There are 16 identical circuits on the board. This circuit block contains 2 MOSFETs as a switching element, the gate driver IC that will drive and control this MOSFET, the sense resistor that will be used to measure the current passing through the channel, and the necessary output protection algorithms, analog voltage, and current measurement circuits.

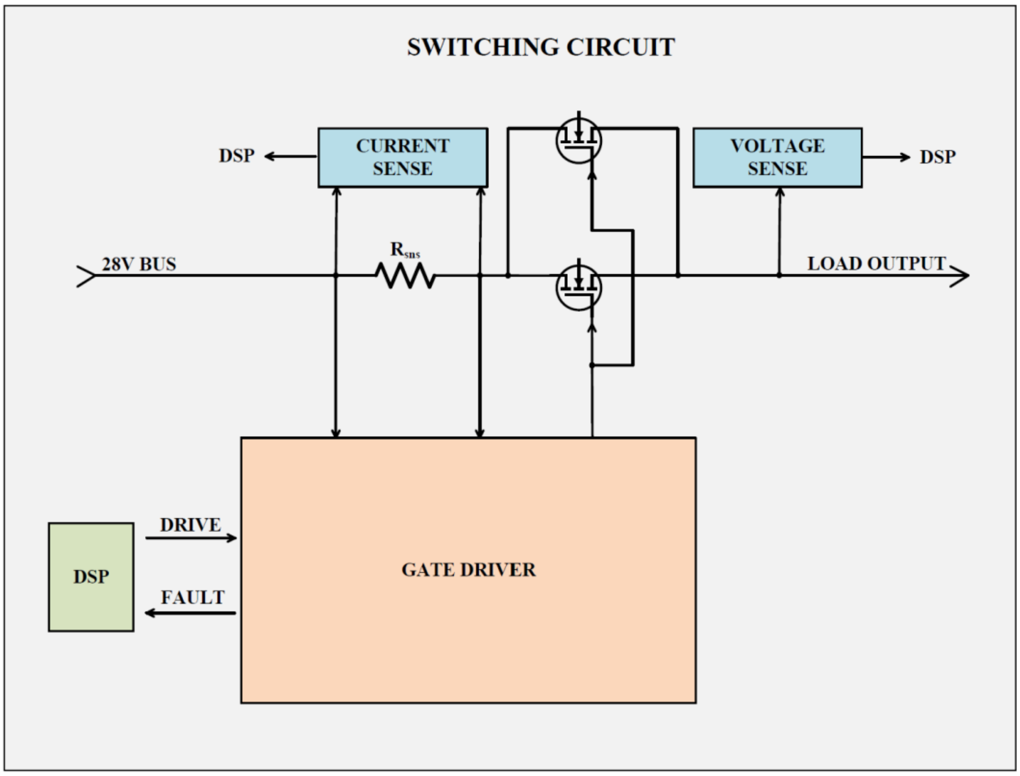

Figure 10: SSPC Load Switch Circuit

The short-circuit protection at the outputs is implemented both in hardware and software. There is a sense resistor in front of the MOSFETs used as switches in the channels to measure current. Depending on this resistance value and the amount of current flowing through this resistor, a voltage difference occurs between the two terminals of the resistor. When this voltage exceeds the 75mV threshold, the gate driver stops driving the switch and the output switch is closed. It takes approximately 300us for this shutdown to occur. The short-circuit state will be entered when a current of 800-1000% of the rated current has appeared at the output. By changing the value of the sense resistor to be used in the circuit shown in Figure 10, the short circuit current at which the outputs will be turned off can be adjusted. The channels on the SSPC have a certain output current rating. These range from 8A, 10A and 25A. According to these current ratings, the resistance values to be used are determined with the following formulas.

$$V_{(SENS+)} - V_{(SENS-)} = \Delta V_{TH} \tag{3.1}$$

$$\Delta V_{TH} = I_{(SHORT)} \times \mathrm{R}_{(SENSE)} \tag{3.2}$$

Table 2: Hardware Short-Circuit Trip Values

Maximum Channel Current	Short-Circuit Current	Short-Circuit Trip Percentage
8A	80A	800-1000%
10A	100A	800-1000%
25A	250A	800-1000%

3.3 Auxiliary Circuits

SSPC has discrete control input and output circuits as auxiliary circuits. These circuits can be used for hardware communication in case the CAN-BUS or RS485 lines used for communication are lost and add some extra software features to SSPC. 8 of these circuits are input and 2 of them are output. The circuit structure used as output is shown in Figure 11, and the circuit structure used as input is shown in Figure 12.

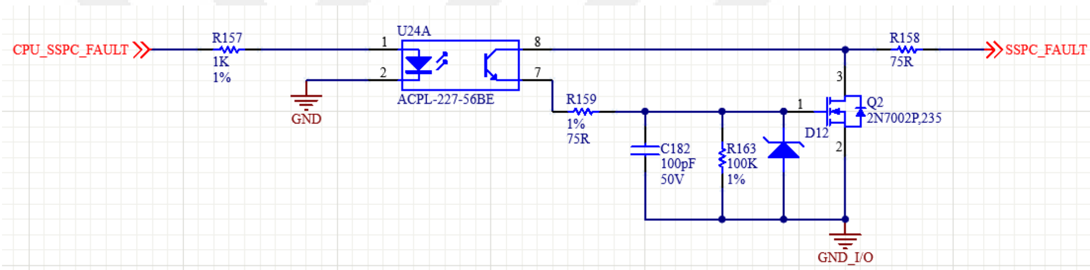

Figure 11: Discrete Output Interface

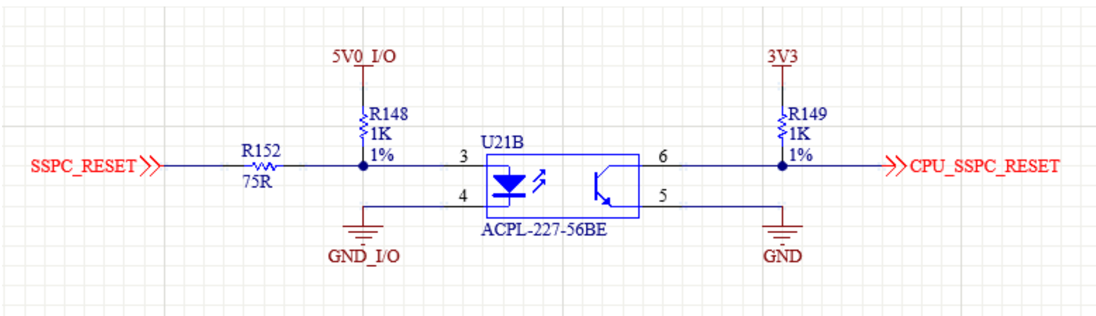

Figure 12: Discrete Input Interface

One of the discrete input circuits is named BATTLE_SHORT. When the signal comes from this circuit, the faults in the SSPDU are ignored and the power distribution unit is operationally operated. To give an example of this situation, the input voltage is lower than normal, in this case, the software does not allow the SSPC outputs to be opened. However, if this BATTLE_SHORT signal is active, SSPC can ignore this error and open the outputs. Another defined discrete input signal is the EMERGENCY_SHUTDOWN signal. When this signal is active, all outputs are closed instantly. It is not possible to open the outputs unless the signal is cleared. SSPC_MODE_1 and SSPC_MODE_2 which are discrete input signals are used together. The logic state combinations of these two circuits are used to create four different modes for the SSPC. Detailed mode usage is explained in Section 4.1.6. If the SSPC_RESET signal is activated and SSPC operates in a mode, all opened outputs will close. After all the outputs are closed, the outputs will be opened again after the delay times defined in the mode. Apart from the discrete inputs whose properties are mentioned, there are three more identical circuits. A desired software feature can be assigned according to the user's request.

One of the discrete output circuits is defined as SSPC_FAULT. It sends out a signal in case of temperature error, input voltage error, or channel output error in SSPC. A desired software feature can be added to the other circuit on the board.

3.4 PCB Design

A total of 238A power distribution is planned for 16 channels with SSPC. It is designed so that the power input is through the connector located in the middle of the PCB, and the power outputs are transferred to the loads via the connectors located on the right and left sides of the PCB. MOSFETs that will switch power to 16 different output channels are placed on the right and left sides of the board. A busbar is used on the top of the PCB to carry power from the power input connector located in the middle of the PCB to these channels. Thus, it is possible to carry power from MOSFETs to output connectors in the layout. The designed input busbar model is given in Figure 13 Again, busbars are used to carry power from the output MOSFETs to the connectors. Model of one of the designed output busbars is given in Figure 14

Figure 13: SSPC Input Busbar Model

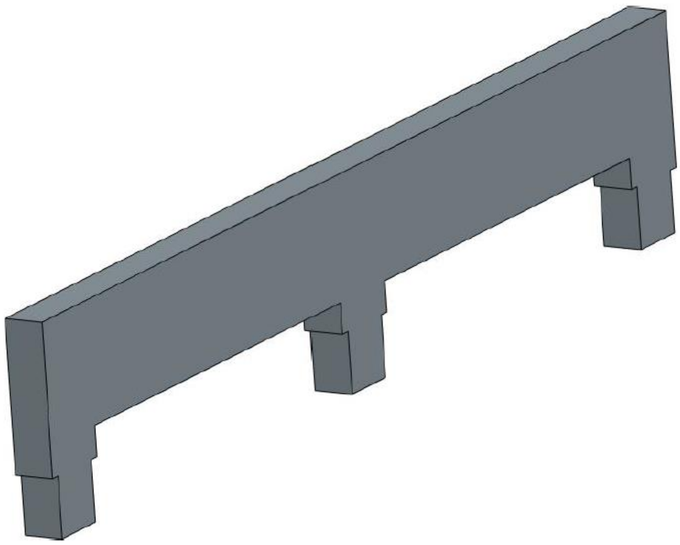

Figure 14: SSPC Output Channel Busbar Model

The designed PCB can be seen in Figure 15. The design has been implemented on an 8-layer PCB. Since the PCB has high current lines, the inner and outer layer copper thicknesses are used as 2 oz. PCB surface coating was chosen as ENIG because of better oxidation resistance, electrical performance, high-temperature resistance and better shelf life than HASL or ENEPIG coatings [6]. Altium Designer (21.9.2) PCB Design software was used to design the PCB.

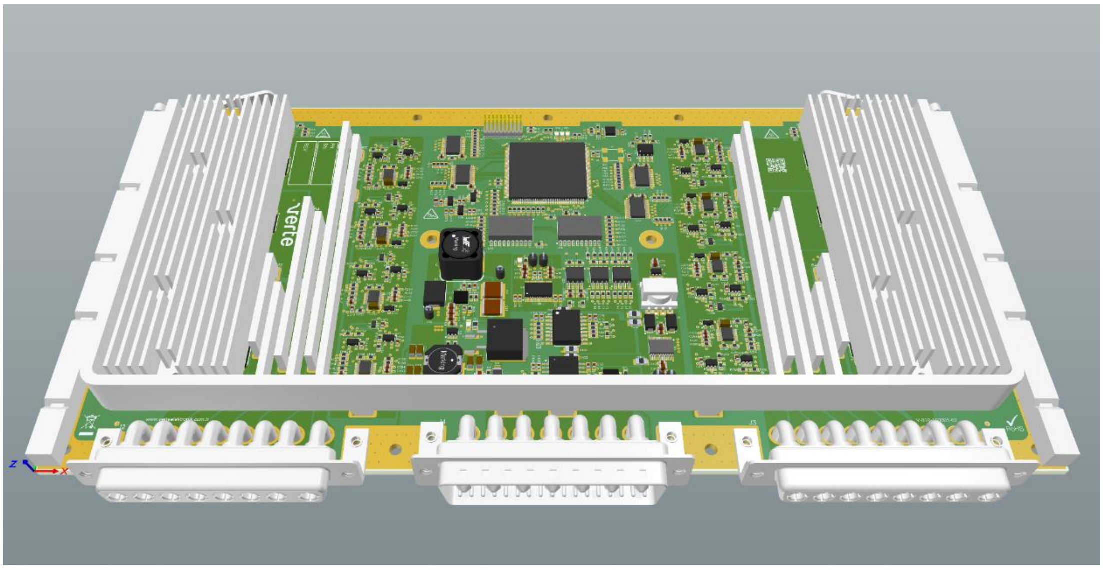

Figure 15: SSPC PCB 3-D view

3.5 Mechanical Design

While designing SSPC, it was planned to be a solution for SPDUs that need more output power using both stand-alone and multiple SSPCs together. It has been designed to a size that can fit in a 6U standard rack. In this way, more than one SSPC can be installed in a single rack according to the number of needs. The dimensions of the mechanical design are given in Figure 16 and Figure 17.

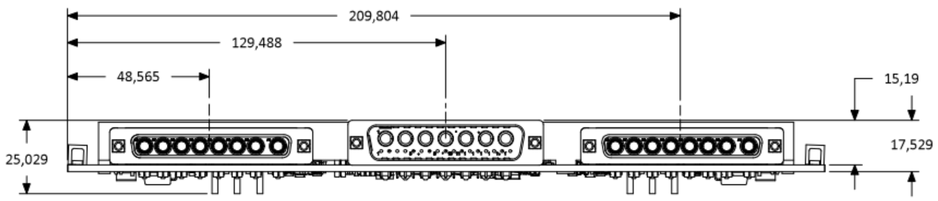

Figure 16: SSPC Mechanical Dimensions-1

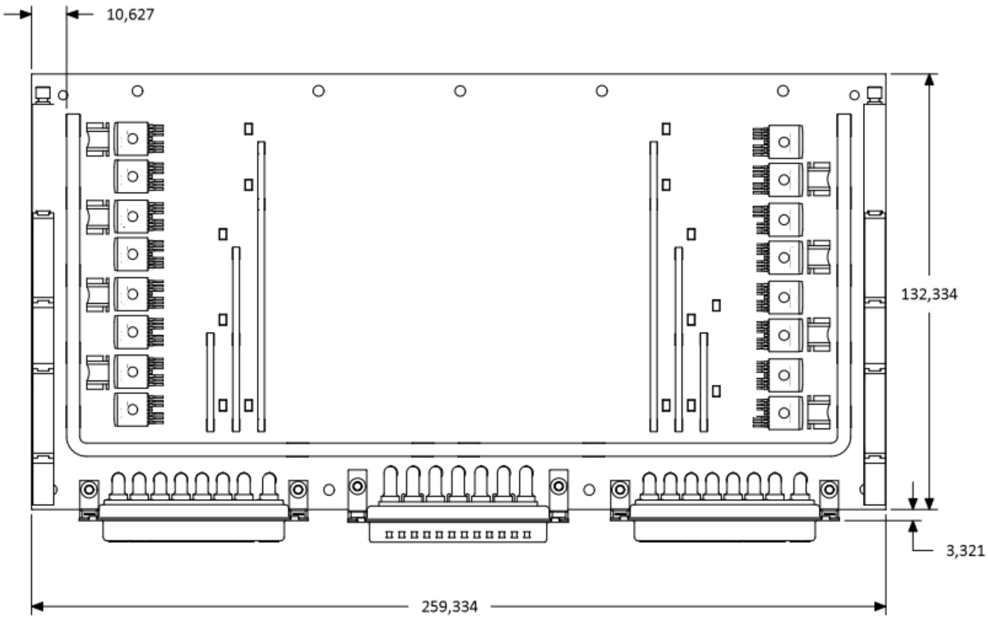

Figure 17: SSPC Mechanical Dimensions-2

CHAPTER IV
SOFTWARE DESIGN OF SSPC

Nowadays, a variety of communication buses are used. For our design, a communication infrastructure that is robust, reliable and allows communication between more than one SSPC was required. Considering that the possible places where SSPC can be used are aviation, military vehicles and industrial environments, it was decided to choose RS485/RS422 and CAN-BUS communication infrastructure.

RS485 is a physical (electrical) communications standard published in 1983 by the Telecommunications Industry Association (TIA) and the Electronic Industries Alliance (EIA) [7]. One of the main features that led us to choose RS485 is that this communication protocol supports up to 32 nodes. In configurations where more than one SSPC are used together, this feature is required.

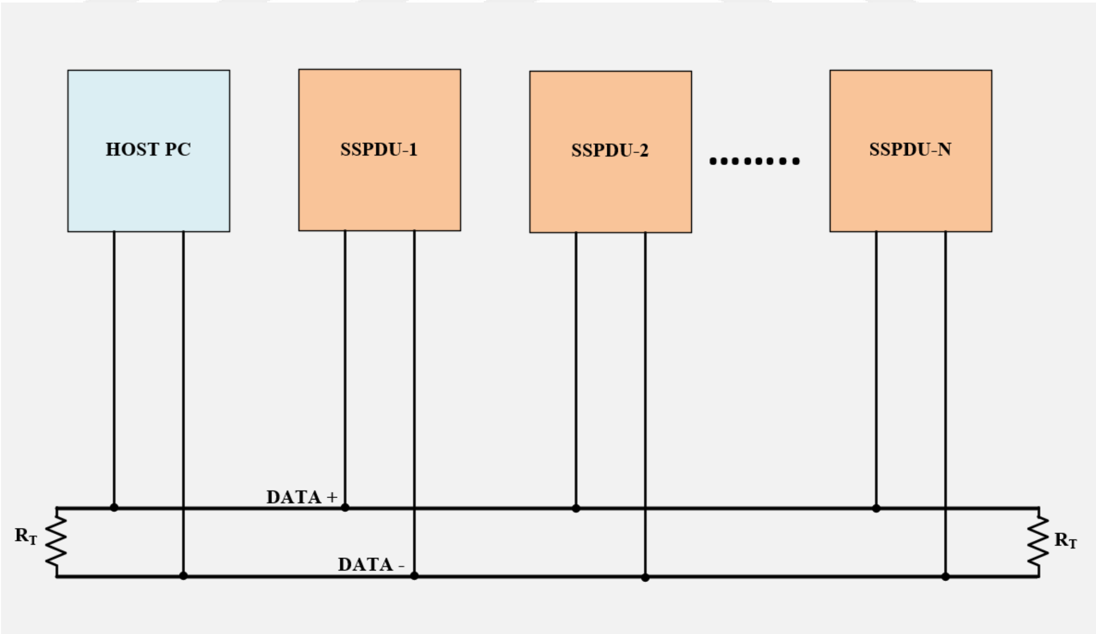

Figure 18: Typical Multiple SSPC at one RS485 Communication Line

In addition, RS485 is a good option for SSPC, which is used in relatively large environments such as aircraft, and military vehicles, to provide safe and high-speed transmission of data as a result of the long harness of communication lines. 10Mpbs data transmission rate can be reached at 40 feet [7]. Again, RS485 can be used in two different configurations half-duplex and full-duplex. In full-duplex use, there are four signal lines, two of which are differential signal cables. Two of these signal lines are used by the master for data transmission and two for data reception. Thus, both data transmission and data reception can be done instantly. In the half-duplex configuration, there are two signal lines and one differential. Since data is sent and received over the same lines, control signals are used for the use of the data bus [7]. In order to provide flexibility in the design, a transceiver is used to provide both full-duplex and half-duplex communication. The PCB lines are drawn to the connectors of the SSPC card in such a way that it can provide a full duplex connection. In current usage, RS485 is used as a half-duplex by using jumper resistors on the printed circuit board.

Another selected communication interface CAN-BUS was developed by BOSCH [8]. CAN is a multi-master, two-wire differential pair communication protocol. The High-Speed ISO 11898 Standard provides a bus length of 40 m, a maximum of 30 nodes, and a maximum signaling rate of 1 Mbps [8]. As shown in Figure 19, it is terminated at both ends with 120Ω resistors matching the line's characteristic impedance to avoid signal reflections [8].

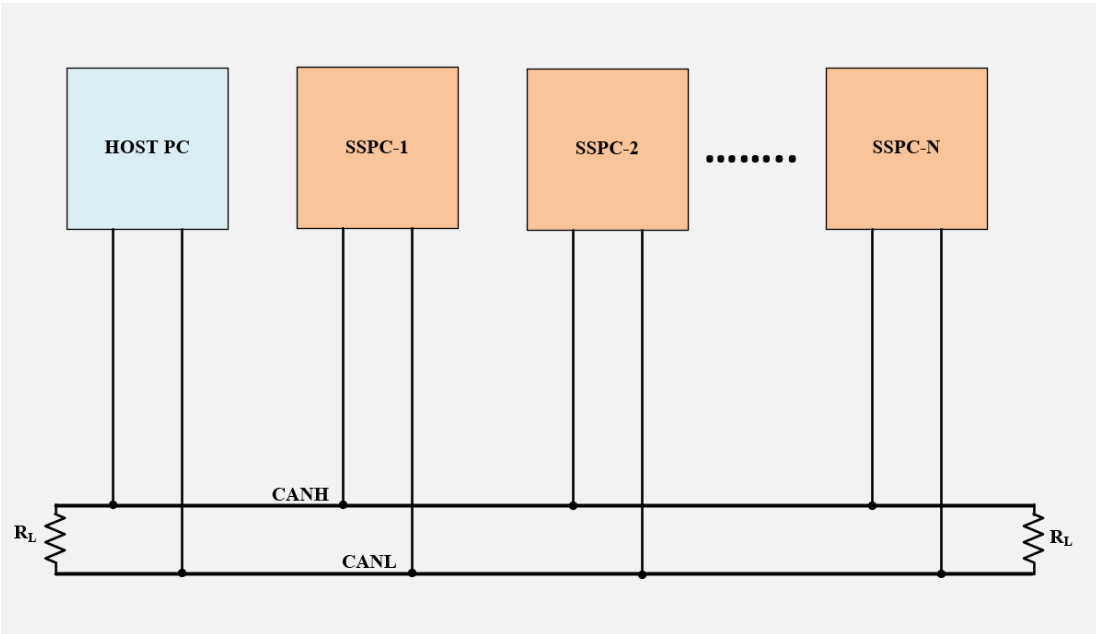

Figure 19: Typical Multiple SSPC at one CAN-BUS Communication Line

4.1 Software Features

One of the most important features of SSPC is its property of having an intelligent software. This software adds controllability, traceability, configurability and on-load protection to the power distribution unit. The SSPC communicates with a PC interface software over the previously mentioned RS485 and CAN-BUS communication protocols, so these features can be used by the user in real-time. Both embedded and computer software have been developed with the plan that multiple SSPCs can be used within the same unit. SSPCs assigned with different IDs can be controlled via single computer software. The communication protocols that have been developed allow SSPC to be controlled by any proper computer. A windows based graphical user interface designed according to this protocol is shown in Figure 20. The GUI software makes it easier to understand the SSPCs software functions. Furthermore, this tool will provide ease of use for a wide range of end users in the field. The features of SSPC will be explained using this designed GUI program. End users can also develop their own control software within the scope of the protocol. Currently, only serial communication (RS485) option is available on SSPC and GUI. The CAN communication interface is not yet active.

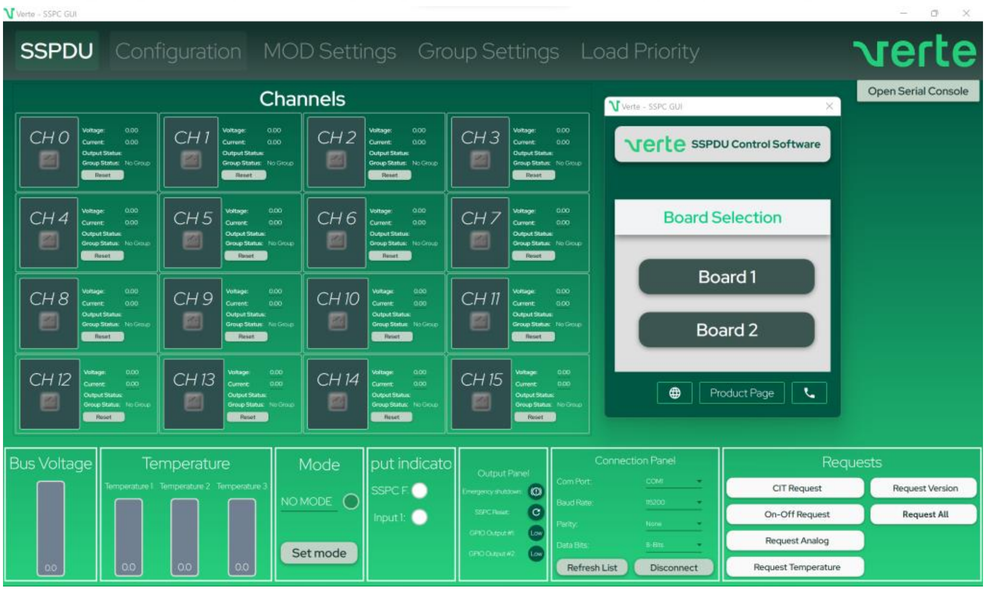

Figure 20: Main Page of SSPC GUI

Several RS485 parameters must be established in order to communicate with SSPC. The necessary settings are given in Table 3.

Table 3: RS485 Settings

RS485 Settings	Unit	Value
Baud Rate	Bd	115200
Data Bits	Bit	8
Parity	-	None
Stop Bits	Bit	2
Flow Control	-	None

4.1.1 Serial Communication Protocol

The serial communication is ASCII coded. Every RS422/485 message starts with the “STX” character, ends with the “ETX” character. Detailed protocol specifications are given in Table 4.

Table 4: Serial Communication Protocol

STX	ID	Resource No	Data Length	Data	LRC	ETX
1 byte	1 byte	1 byte	4 bytes	Data Length Byte	2 bytes	1 byte
0x02	ASCII from '!' to '~' can take 94 values	ASCII from '!' to '~' can take 94 values	ASCII representing hex digits (MSB first)	ASCII representing hex digits (MSB first)	ASCII representing hex digits (MSB first)	0x03

A system can have more than one SSPC. Each SSPC will have its own ID to allow communication over the same RS485 line. In single card configuration, the ID is '1'. The ID values that can be assigned to SSPCs are given in Table 5.

Table 5: SSPC ID

ID	
SSPC 1	‘1’
SSPC 2	‘2’
SSPC 3	‘3’
SSPC 4	‘4’

SSPC message contains a variety of information. Output channel turn-on and turn-off messages, analog output channel values, and configuration settings uploaded to the SSPC are a few examples of these. This information has been divided up into individual packages as a result and given in Table 6. Request, command, response, and NACK messages are the four main groups of message packets that can be inspected.

A command message packet is issued by the host when the SSPC is requested to perform a task. These command messages can also contain instructions to switched-on or switched-off the output channels or to load any configuration into the SSPDU.

The request message is sent by the host whenever it needs to obtain any information about the SSPC. These request messages receive a response message from SSPC.

NACK message is sent or received in case of any message that does not compliant with the SSPC communication protocol.

Table 6: SSPC Resource No

Resource No		
Message Name	**ID**	**Direction**
Status Request	‘a’	HOST --> SSPC
Status Response	‘b’	SSPC --> HOST
On/Off Command	‘c’	HOST --> SSPC
On/Off Request	‘d’	HOST --> SSPC
On/Off Response	‘e’	SSPC --> HOST
Analog Data Request	‘f’	HOST --> SSPC
Analog Data Response	‘g’	SSPC --> HOST
Temperature Request	‘h’	HOST --> SSPC
Temperature Response	‘i’	SSPC --> HOST
Reset Command	‘j’	HOST --> SSPC
Version Request	‘k’	HOST --> SSPC
Version Response	‘l’	SSPC --> HOST
Config Settings Command	‘m’	HOST --> SSPC
Config Settings Request	‘n’	HOST --> SSPC
Config Settings Response	‘o’	SSPC --> HOST
Group Settings Command	‘p’	HOST --> SSPC
Group Settings Response	‘q’	SSPC --> HOST
Group Settings Request	‘r’	HOST --> SSPC
Mode Settings Command	‘s’	HOST --> SSPC
Mode Settings Request	‘t’	HOST --> SSPC
Mode Settings Response	‘u’	SSPC --> HOST
NACK	‘y’	HOST --> SSPC SSPC --> HOST

4.1.2 Load On/Off

One of the most fundamental features of the embedded software is the ability to turn the load on and off remotely with the communication interfaces. The output turns on or turn off commands sent via GUI are processed by SSPC in case there is no error condition at that time. In addition, the GUI performs an output status query every second to check if the outputs are on or off. Thus, it is verified that the on-off commands sent are processed. If there is a difference between the sent command, switch and output status an output error condition is generated. On the GUI, the error status is indicated at the relevant output channel as seen in Figure 21.

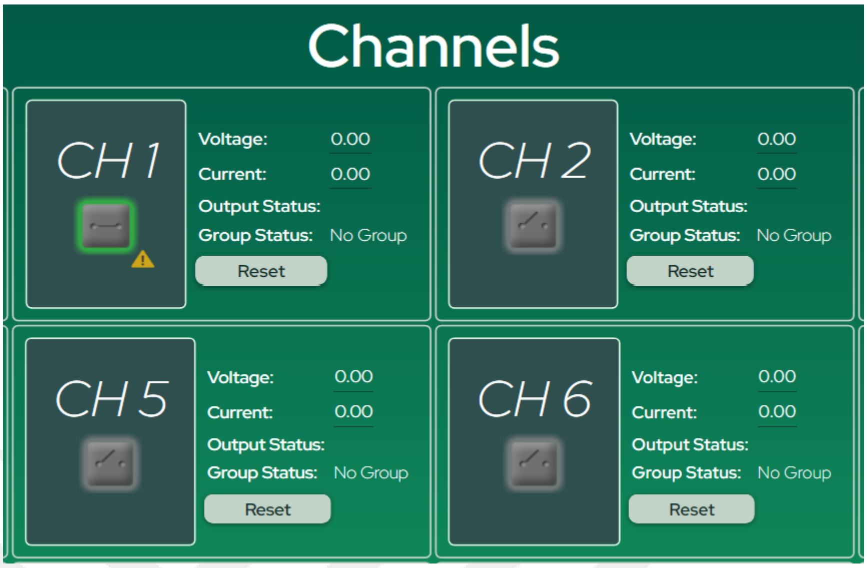

Figure 21: Output Channels Control Panel

4.1.3 Analog Value Traceability

The voltage and current values of all outputs and input bus is measured analogously by the microcontroller. As a result of the analog data query made by GUI, the user can observe the voltage and current values of all outputs and bus instantaneously.

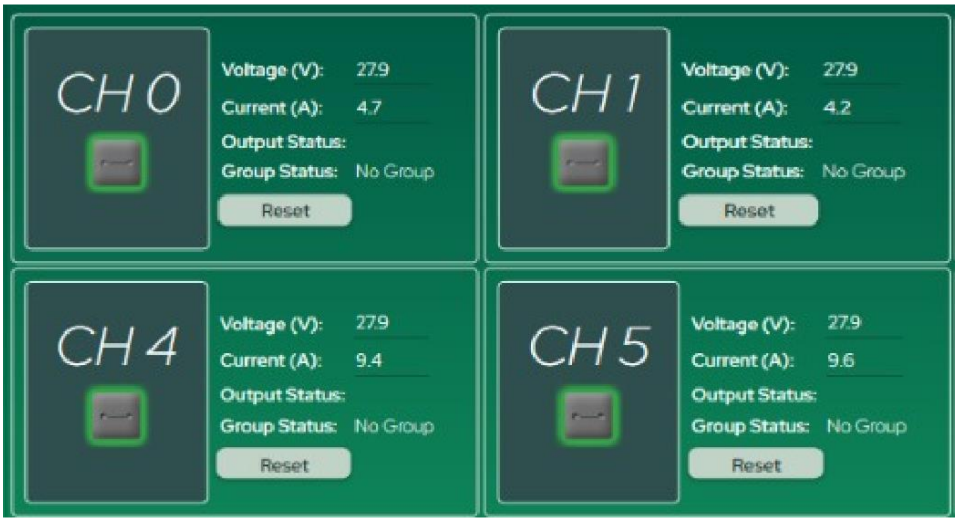

Figure 22: Realtime Channel Voltage and Current Measurement

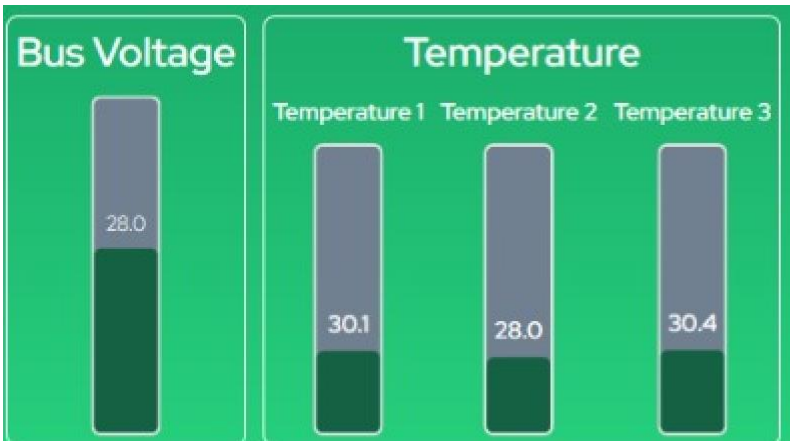

Figure 23: Realtime Input Voltage and Board Temperature Measurement

4.1.4 Fault Condition Detection

In order for the system to work reliably, the SSPC should be able to detect unwanted error situations in detail. The more detailed the error can be detected, the easier it is to find a solution. SSPC error states such as high-low input voltage, high-low board temperature, high-low channel voltage, output short circuit condition, output overload condition and output trip current error can be detected. In addition, output error detection can be made as a result of the incompatibility between the command sent to the SSPC and the current states of the output switch. In this case it can be said that there is a hardware error.

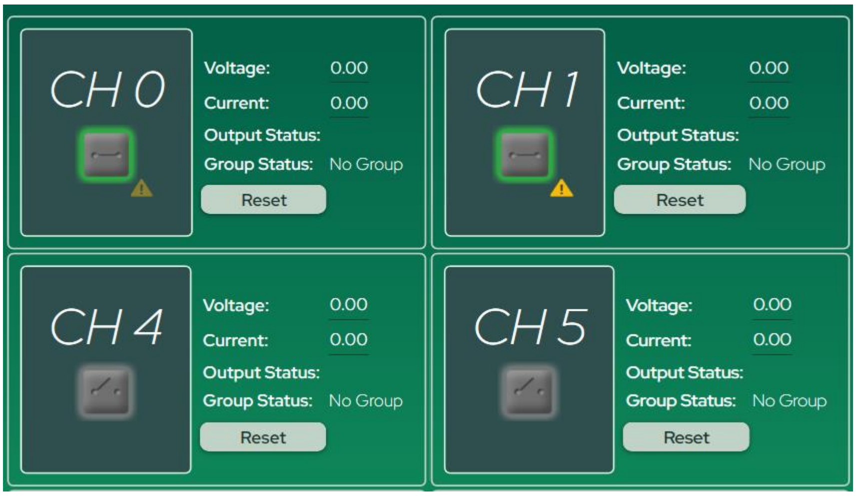

Figure 24: Realtime Channels Error Detection

4.1.5 Import and Export Configuration

All of the user's configuration data can be stored on the SSPC due to the onboard EEPROM in the board. Through configuration command messages, desired settings can be processed to the SSPC. Configuration data saved in SSPC can be retrieved with request messages. These request messages receive a response message from SSPC.

4.1.6 Mode Selection

In terms of ease of usage, SSPC has features to use in three different modes. These modes can be made both through the discrete inputs on the SSPC and software via the GUI. Power distribution units may have a certain working pattern according to the place they are used. Certain outputs may need to be turned on in a certain order. To give an example, outputs of channel 1 and channel 2 outputs are used for different parts of same system. Also, the load fed from CH1 needs to be turned on before the load fed from CH2 and it takes 20 seconds to become fully operational. In this case when defining the mode, the powering-on sequence delay CH1 can be defined as 0 seconds and the delay of CH2 can be defined as 20 seconds. When the operator puts the SSPC in mode, CH1 will be opened directly, after 20 seconds CH2 will be turned on automatically. It may also be possible to name these situations as maintenance, operational, setup in GUI. Mode definitions are made on the GUI for one time only. Which outputs will be opened in which order in the mode to be defined, this is assigned and sent to the SSPC. The user selects the mode they want to set and enters the outputs and opening delays they want to use in this mode. SSPC stores this data in its internal EEPROM. Therefore, even after SSPC is turned off and turned on, mode features remain saved. The delay feature can be adjusted at 100ms resolution. When the mode feature is not desired to be used, each output and group can be switched on and off momentarily. Figure 25 illustrates the mode selection panel that has been prepared on the GUI.

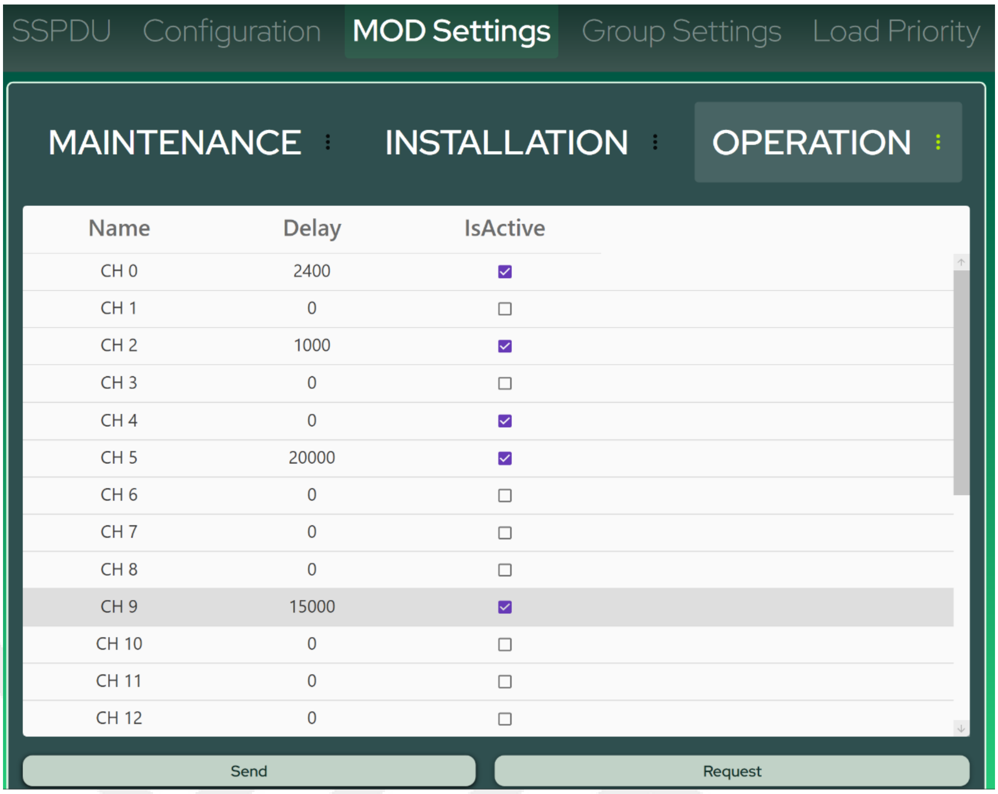

Figure 25: Mode Configuration Settings

4.1.7 Channel Grouping

The current ratings of the 16 channels in the SSPC are divided into three groups 8A, 10A and 25A. The channels in which these current ratings can be used are defined by software. When the user needs more power than these maximum channel current values, the needed desired power can be met by paralleling the channels of the SSPC. Channels within the group are opened and closed at the same time. Channel paralleling can be done up to 8 different groups. The created groups will have all the features such as mode, I^2T, current trip in channels in SSPC. For example, channel 3 and channel 4, which are two different outputs with a 30A rating, can be set as group 1 and output current rating increase to 50A. It can be assigned this group to any mode to use it in any mode and define a power-on delay time. Channel grouping configurations are also stored in the internal EEPROM.

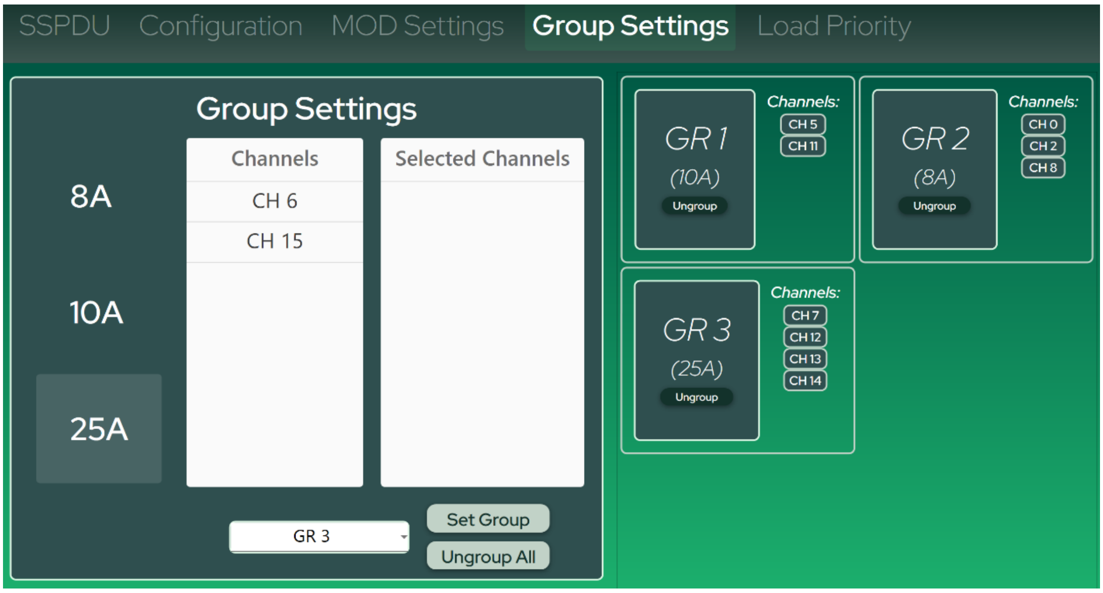

Figure 26: Channel Grouping Settings

4.1.8 Channel Reset

The delay times assigned to the outputs for mode usage can also be used to reset the outputs. When the reset message is sent to the channel to be reset while the output is open, the output is closed and then it is opened again at the end of the delay time registered in the SSPC. For this message to be applied, the SSPC must be operating in the predefined mode.

4.1.9 GPIO Status Indication

SSPC has 8 discrete inputs and two discrete outputs. One of the discrete input circuits is reserved for battle short, one for SSPC reset, one for emergency stop, two for mode usage. The remaining three discrete input circuits are ready for use for any desired feature assignment. Instead of these circuits assigned to a certain function in hardware, these operations can also be performed in software via the GUI. One of the two discrete output circuits is paired with the SSPC fault function. In case of any error in the SSPC (high-low temperature, high-low input voltage, high-low board temperature), it can be read through the hardware discrete output circuit, and the status of this circuit can be observed through the software GUI.

4.1.10 I^2T and Current Trip Settings

The SSPC's adjustable I^2T protection is one of its main benefits to the user. Thanks to the I^2T adjustment it makes, it can prevent the power distribution unit from falling into error due to the inrush current drawn by the load it feeds. Maximum inrush current, inrush time and normal current rating parameters from the characteristics of the load are sent to the SSPC. Thanks to the I^2T calculations made continuously in the SSPC, the output is prevented from getting into error during the allowed inrush current and time.

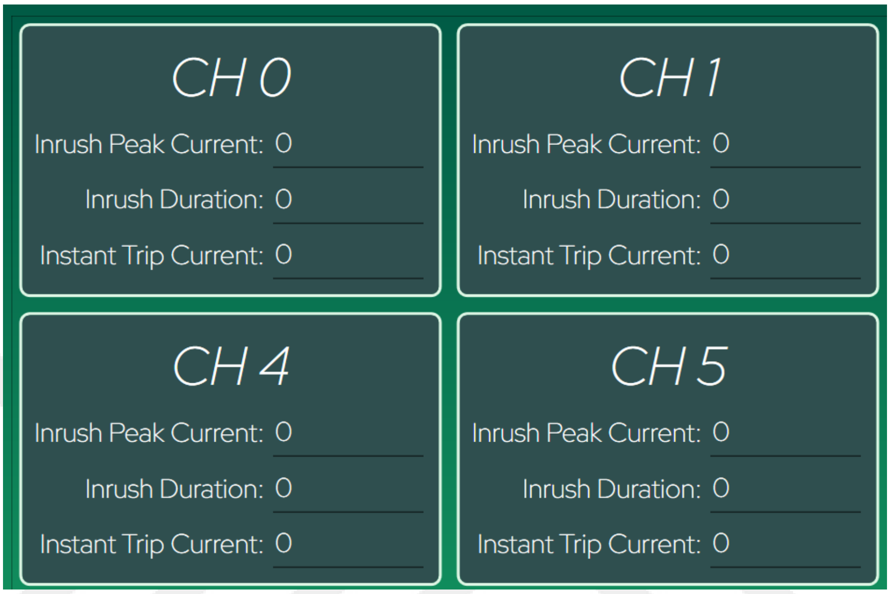

Figure 27: Output Channels I^2T Settings

4.2 Software Protection Algorithms

4.2.1 I^2T Protection

Short-duration irregularly shaped current pulses can have severe effects on the conductors and electronics they pass through [10]. Additionally, some loads, like motors, may start out drawing a significant amount of current for a brief period of time. Due to this current drawn more than normal at the beginning, the output may enter the error state and the output may be shut down. To prevent this, the I^2T algorithm can be used. The level at which this current will damage electronic equipment or cables can be called an instantaneous trip region. By subtracting the square of the rated current from the square of this limit current, the I^2T algorithm adds in real time over time t. An overload occurs when this total is equal to the maximum value that will not damage equipment or cables beforehand. A typical I^2T curve is given in Figure 28.

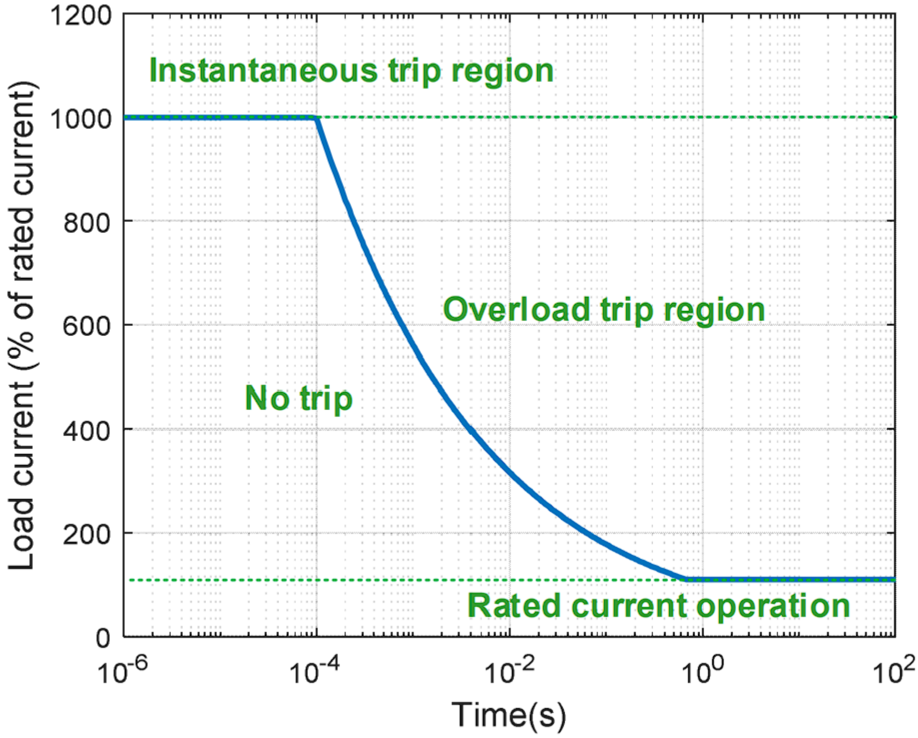

Figure 28: Typical I^2T Curve [12]

4.2.2 Current Trip and Short Circuit Protection

The SSPC also has current trip protection and software-based short circuit protection in addition to analog short circuit protection. DSP performs current measurements in real-time. In embedded software, DSP performs current sampling in 100µs intervals. In these periods, the output is turned off immediately when a current of 10 times of a predefined maximum current value such as 8A, 10A or 25A is measured. The user sets a trip current for current trip protection that is no greater than the channel maximum current. The output shuts automatically when the channel reaches this value.

4.2.3 Emergency Stop

This function can be activated by both software and hardware via a discrete control pin. This mode can be activated when there is a critical situation or when the output channels or groups turn off immediately.

4.2.4 Battle Override

SSPC has features Battle Override to work in critical situations. This mode can be activated both software and hardware via discrete control pins. When Battle override is activated, the SSPC ignores all other conditions which are voltage error, temperature error, I^2T error, except short-circuit, preventing the outputs from turning off or allowing the turning of outputs in case of failure.

4.2.5 Temperature Error

Board temperature is measured instantaneously from three different temperature sensors on the SSPC. All outputs are turned off if this temperature exceeds the allowed high-temperature value or falls below the allowed low-temperature value. If the SSPC is operating in a mode and the temperature returns to the acceptable value, the previously turned-on outputs start to turn on again with the predefined delay times.

4.2.6 Input Voltage Error

The user can set the input voltage range that wants to work within certain limits. For this, the user defines the minimum and maximum input voltage values allowed to the SSPC. The SSPC measures the input voltage continuously. It turns off the open outputs when the input voltage falls below the defined minimum operating voltage or exceeds the maximum operating voltage. Again, if the input voltage is outside these limits, the output SSPC does not allow turn-on output. If the SSPC is operating in a mode and the temperature returns to the acceptable value, the previously turned-on outputs start to turn on again with the predefined delay time

CHAPTER V
PRACTICAL STUDIES

5.1 I^2T Protection

The I2T protection algorithm has been tested on one of the channels in the SSPC. The rated current of the channel is set to 5A. Software modeling has been made so that the channel shut down in 5 seconds at 200% of the nominal current value. All parameters are set via the GUI described in previous chapters. In Figure 29, it is observed that the output turns off in 5 seconds under a constant 10A load current.

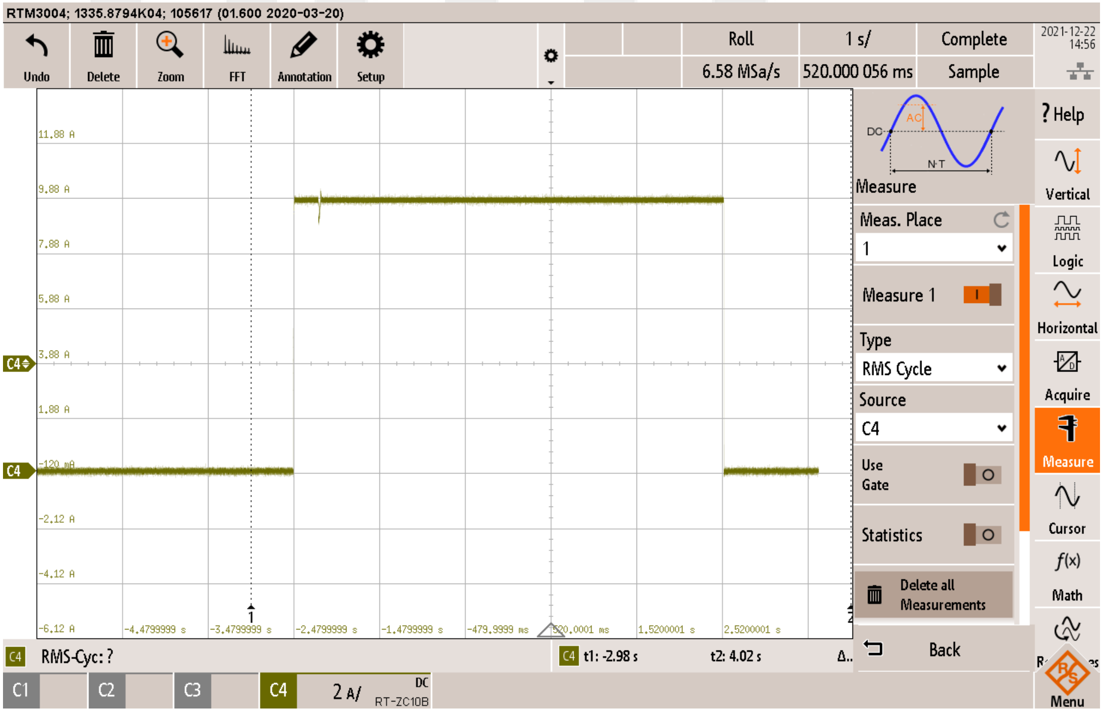

Figure 29: Continuous 10A Output Current I^2T Fault Timing

According to the I^2T modeling, it was expected to turn off the output in 1.875 seconds under a 15A high current. As seen in Figure 30, the output was turned off in 1.873 seconds.

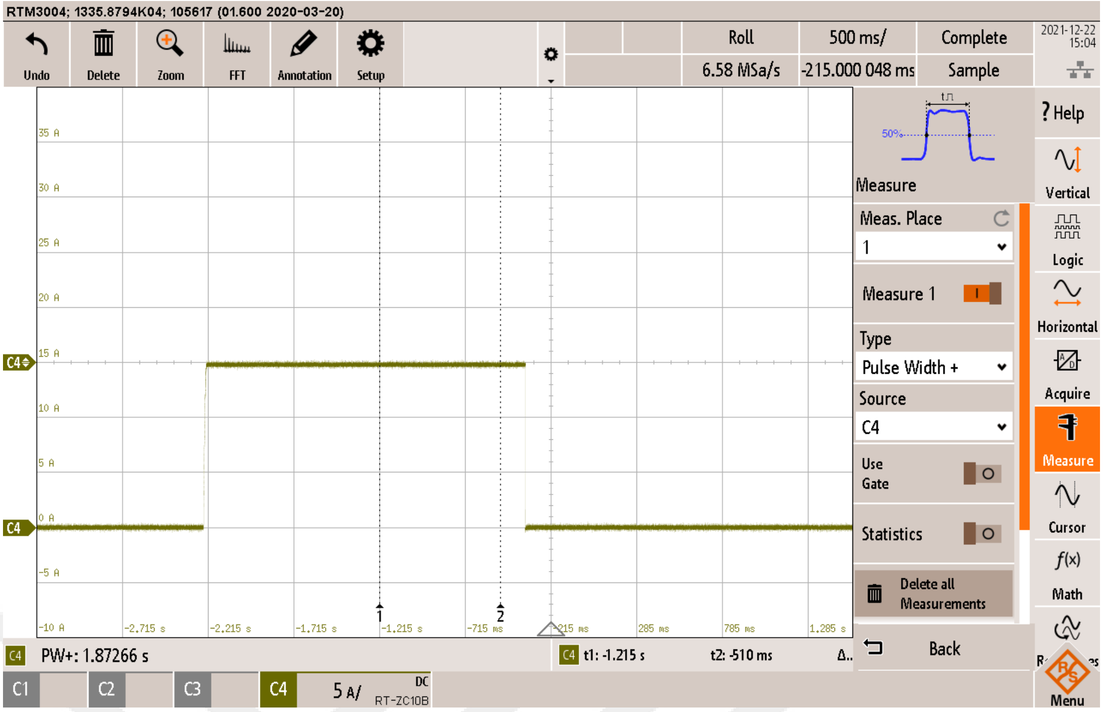

Figure 30: Continuous 15A Output Current I^{2}T Fault Timing

The output must be shut down after 15 seconds under 200ms 0-10A pulsed load current. The output is switched off at the desired moment, as seen in Figure 31.

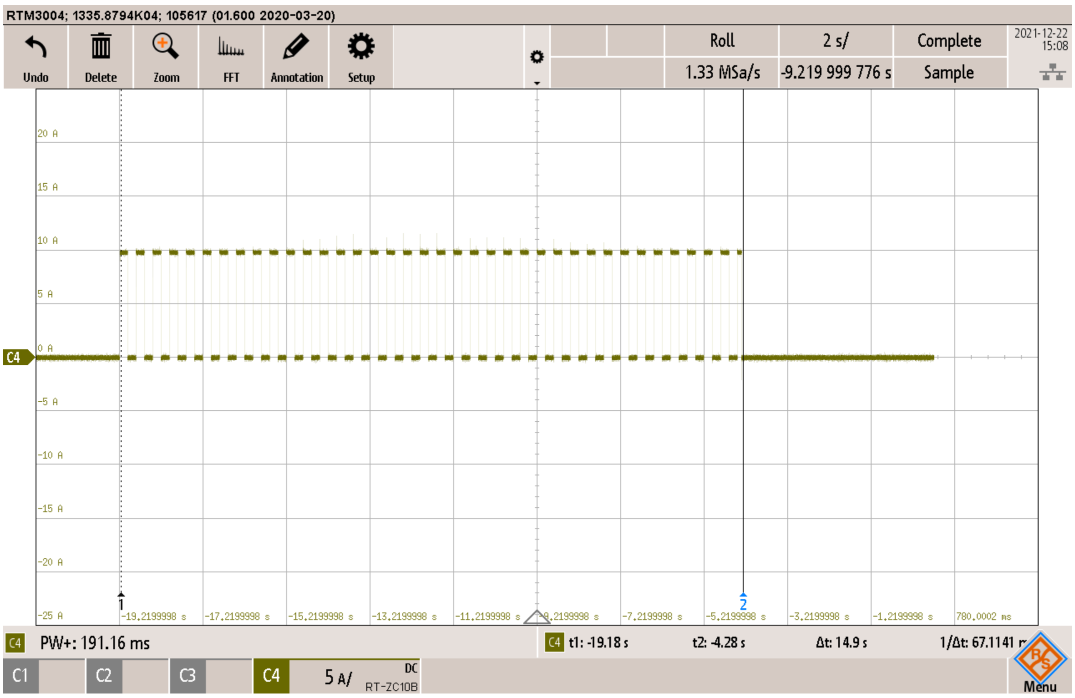

Figure 31: Pulsed 10A Output Current I^{2}T Fault Timing

5.2 Short Circuit Protection

In this part, SSPC's hardware-based short circuit protection is tested. The step-by-step current value over the electronic load has been increased by 1000% above the nominal current value of 10A predefined channel. When the current value reaches approximately 95A, the output has entered the short circuit protection and is turned off as shown in Figure 32. The gate driver turns off the output within approximately 142µs after the error value is exceeded.

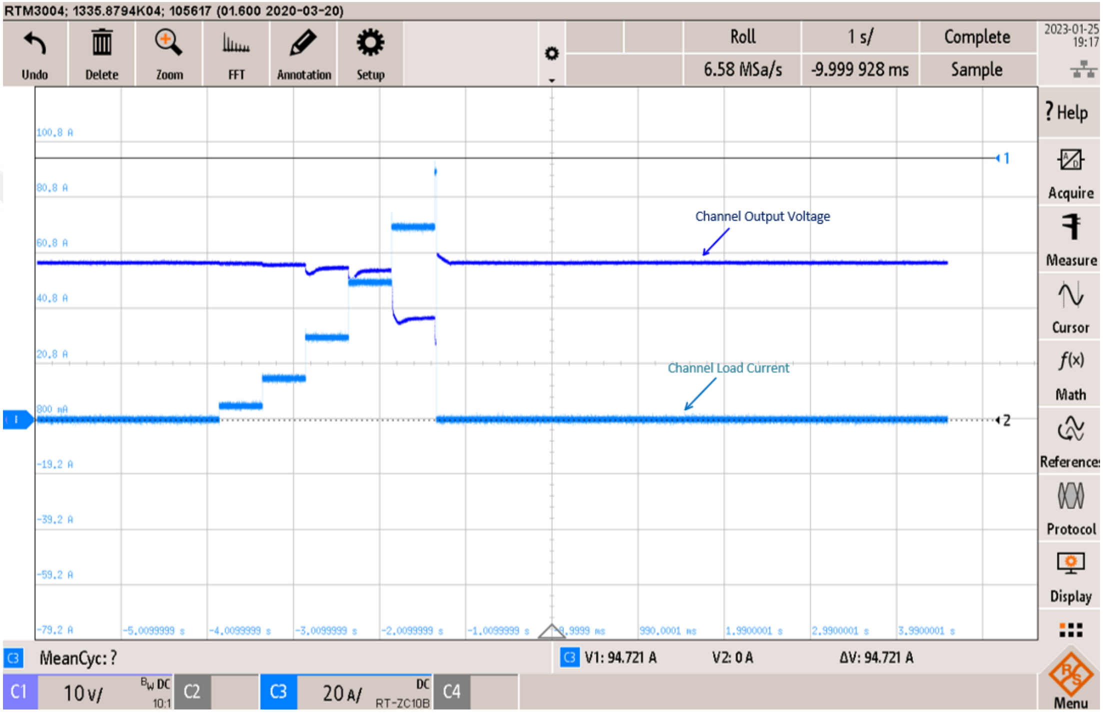

Figure 32: Short Circuit Test for 10A Channel

5.3 Controlled Turn On/Off and Capacitive Load Tests

Individual channel activation and deactivation times for the SSPC are set to be on the order of 1-2ms. As a result, inrush currents for switching into motor, capacitive, or incandescent bulb loads are decreased, which lowers EMI.

Thanks to the controlled channel opening and closing feature of the SSPC, the inrush currents caused by high capacitance loads are also reduced. During the test experiments, studies were carried out with different capacitance values in channels with different current ratings. In Figure 33, the channel with 25A rating is turned on under 7470μF capacitance. With the controlled opening of the MOSFET, the inrush current on the channel is reduced to 110A. Thus, channels feeding high capacitive loads are prevented from false short circuit errors with high inrush current.

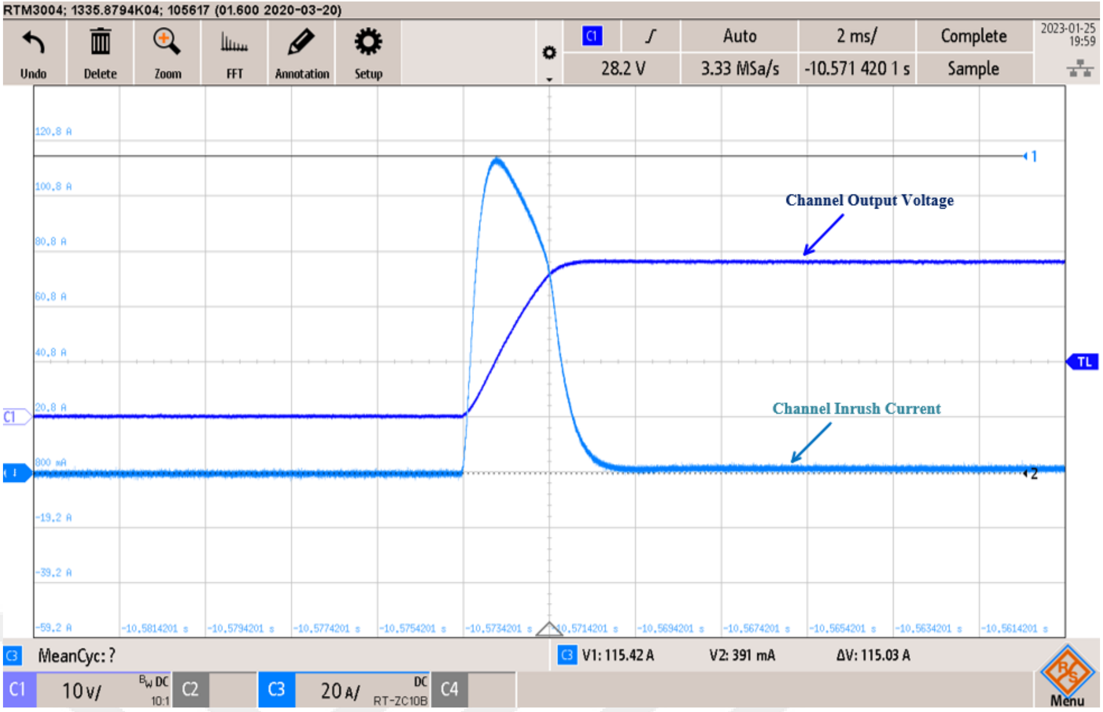

Figure 33: Turning On 7470µF Capacitive Load

The SSPC's 10A-rated channel was tested with a 2960µF capacitive load feeding. As seen in Figure 34, approximately 70A inrush current has occurred on the channel.

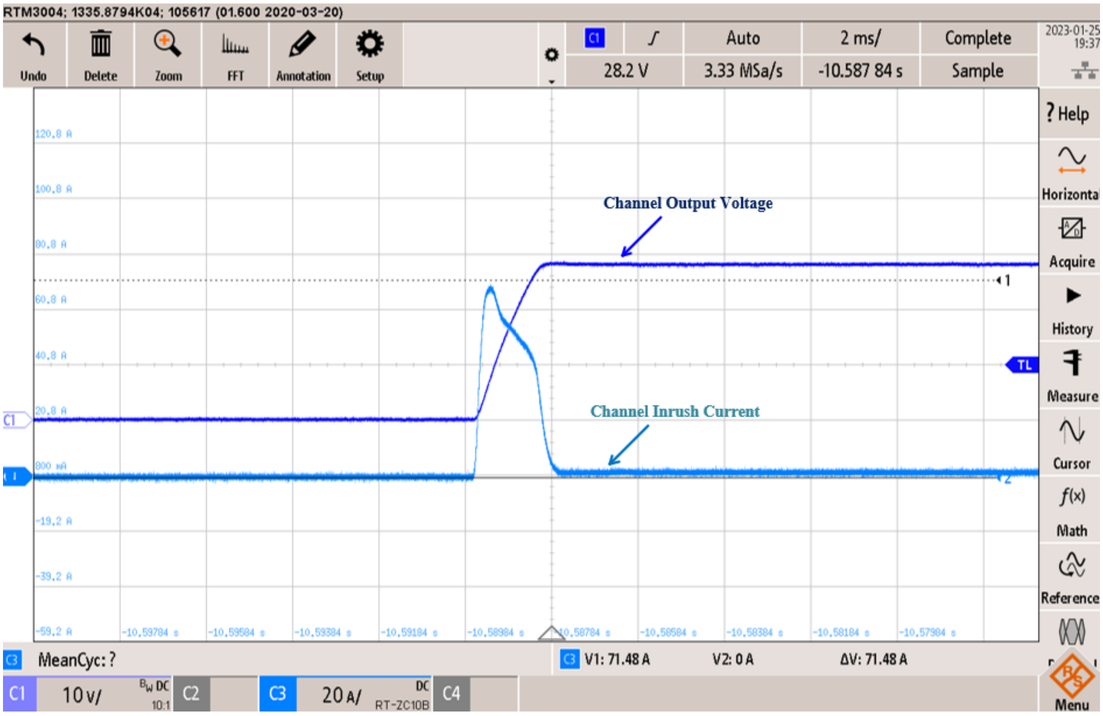

Figure 34: Turning On 2960uF Capacitive Load

The SSPC’s 18A rated channel was tested with a 2960µF capacitive load feeding. As seen in Figure 35, approximately 42A inrush current has occurred on the channel.

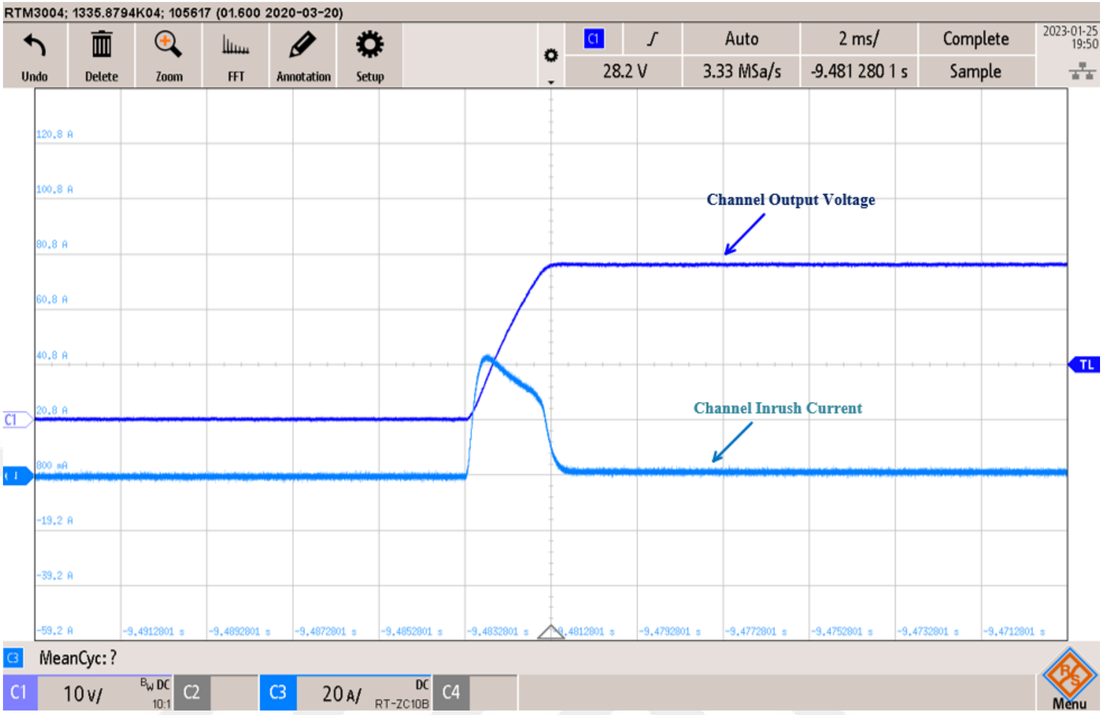

Figure 35: Turning On 2300uF Capacitive Load

5.4 Heat Demonstrations

A test setup has been prepared to verify the SSPC’s ability to distribute 238A power. A resistive load bank has been prepared to be used in the test infrastructure. Each of the 16 channels in the SSPC can be loaded separately at maximum current using the load bank shown in Figure 36. Electro-Automatic's EA-PSI 9080-340 3U laboratory-type power supply was used as the power source.

Figure 36: Resistive Load Bank

All of the SSPCs outputs are connected to the resistive load bank, and each output is loaded separately. To check the SSPC's full load temperature, all outputs were loaded simultaneously. Connections from SSPC are shown in Figure 37.

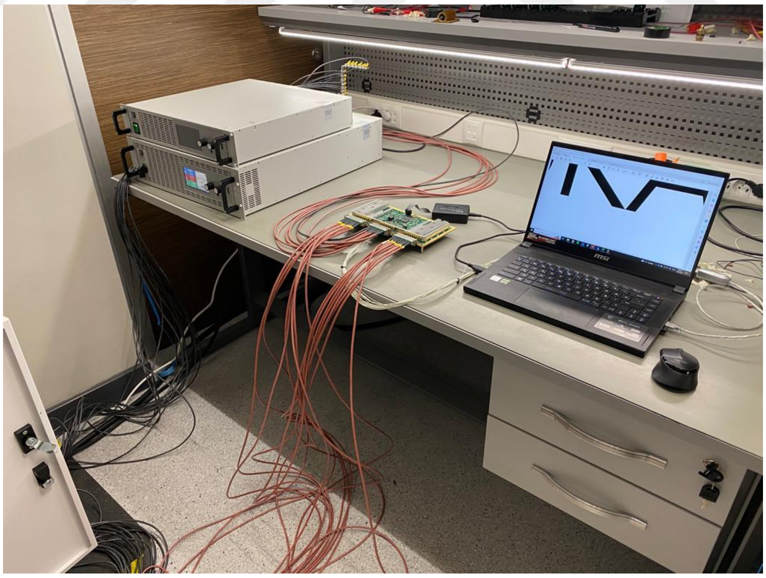

Figure 37: SSPC Output Connections

The output loading test started at 27°C ambient temperature. Both internal temperature sensors and a thermal camera were used to measure the SSPC’s temperature. By turning on the outputs, loading tests were started under 220A as shown in Figure 38. At the end of 35 minutes, the temperature values shown in Figure

39 were taken with the sensors on the PCB. The values of Temperature 1 and Temperature 2 were taken from the sensors located under the heatsink near the output MOSFETs, Temperature 3 shows the data taken from the sensor located in the middle of the PCB, near the processor.

Figure 38: Power Supply Current Consumption

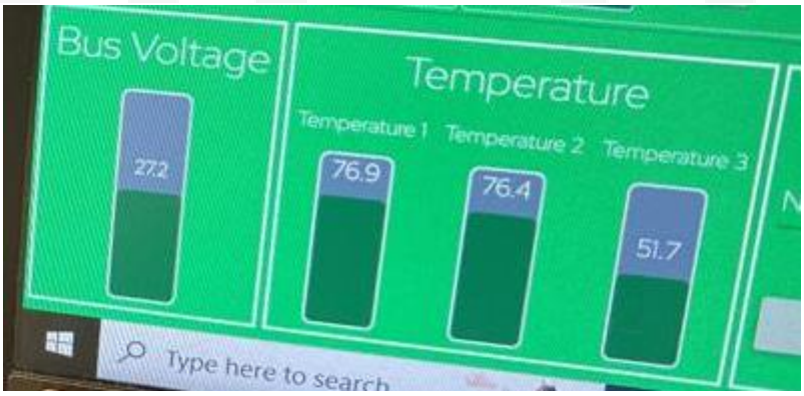

Figure 39: Onboard Temperature Sensors Data

The temperature measurement taken over the heatsink with a thermal camera is given in Figure 40.

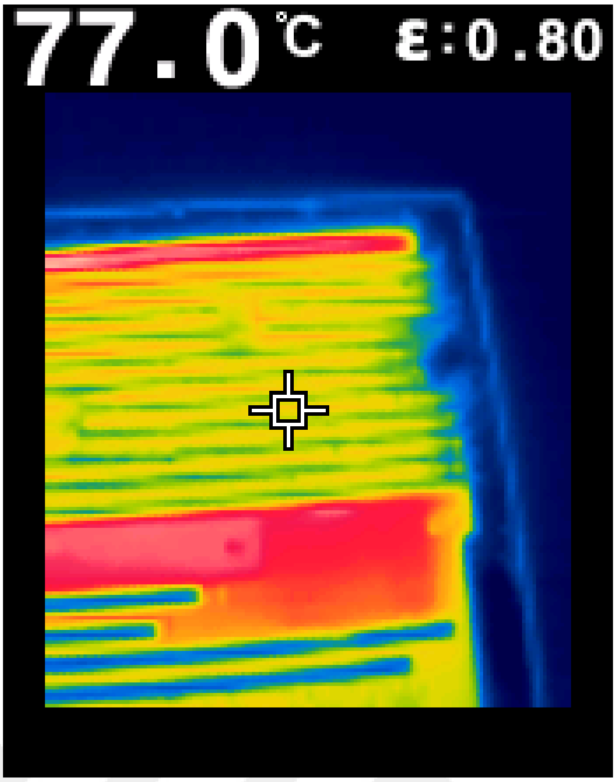

Figure 40: Temperature Measurement on Heatsink

CHAPTER VI
CONCLUSION AND FUTURE WORKS

6.1 Conclusion

The emergence of SI MOSFETs with low drain-source on resistance causes the trend on the power distribution side to shift from traditional power distribution units formed by circuit breakers and electromechanical relays to solid-state power controllers with solid-state switches. Within the scope of this thesis, the power systems of aircraft, which is one of the main areas of use, were examined. It is explained how the power systems of aircraft have been changed with the emergence of SSPCs. A comparison of conventional power distribution systems and SSPDUs, which is called the new generation, has been made. It has been shown that SSPCs are more advantageous in a variety of categories, including weight, size, efficiency, service life, and versatility of use. Again, within the scope of this study, a DSP-based, $28V_{DC}$, 16 channel, 238A output power solid state power controller was designed and implemented.

6.2 Future Works

For the $28V_{DC}$ SSPC, which has been successfully designed and functionally verified, to be used in aviation, necessary certification and redundancy studies are required. Verte Elektronik will support this certification process. The requirements to be encountered during this certification period may cause some changes. For this reason, SSPC may undergo revisions in the production process.

Another planned study is a $270V_{DC}$ solid-state power controller. The concept of more electric aircraft (MEA), which has gained importance today, has pioneered the selection of this voltage value. This concept plans to replace mechanical, hydraulic, and pneumatic systems in conventional aircraft with electrically powered systems [11]. This change significantly increases the power needs of aircraft, resulting in the use of $270V_{DC}$ for high power density. For this relatively high voltage selected value, the switching element and the switch drive circuits will be changed, and the other circuits on the board will be largely similar to the designed $28V_{DC}$ solid-state controller.

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