ZJUI ECE 445

Senior Design Project

Project Proposal

SMART POWER ROUTING WITH MPPT-BASED WIND TURBINE

Project #19

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Change Log

03/07/2024

Ver. 1: Initial submission.

03/11/2024

Ver. 2: The following updates are conducted.

1. Fixed some errors on diagrams (in Figure 2.1).
2. Proposed a new function that allows users to customize output voltage (in §1.3 and §2.2.2).
3. Proposed a new function (in §2.2.9) that allows users to monitor and control the system remotely on their mobile devices.

Abstract

Wind power generation relies heavily on weather conditions. In the era of electronic devices, the market calls for a routing system that switches between wind power and backup power to provide a stable power supply. This paper proposes a wind power generator system with smart power routing which ensures the stability of the power supply. Integrated with the maximum power point tracking (MPPT) technique and a modular multilevel converter (MMC), the generator system aims to provide more sustainability and maintenance convenience.

Keywords: Smart Power Routing, Modular Multilevel Converter, Maximum Power Point Tracking

Contents

1 Introduction

1.1 Background and Problem Statement

In 2023, China's wind power installed capacity reached 441.34 gigawatts, accounting for 15.11% of the total installed capacity for power generation, with a year-on-year increase of 20.7% [1]. This growth trend underscores the escalating demand for wind energy as a renewable power source. Moreover, there's a growing interest among ordinary consumers in small-scale wind power solutions, driven by a desire for decentralized energy generation and environmental sustainability.

However, challenges persist in the wind power sector, including issues of low stability inherent to wind energy, the substantial land footprint required by traditional large-scale installations, and the high maintenance costs associated with such setups. These drawbacks highlight the pressing need for innovative solutions that address the reliability and cost-effectiveness of a small-scale wind power generation system, particularly in the context of smaller, more accessible systems tailored to meet the evolving needs of diverse user groups.

Therefore, the project aims to design a small-scale wind power generation system with power routing functionality. This entails creating a compact and efficient system capable of harnessing wind energy while incorporating mechanisms to seamlessly switch between power sources to ensure an uninterrupted electricity supply. Key objectives include maximizing power output, enhancing system reliability, and optimizing energy management for diverse applications.

1.2 Solution

The envisaged solution endeavors to furnish a comprehensive apparatus of appropriate dimensions tailored to furnish electrical power to consumers residing in regions characterized by significant wind activity. Comprising pre-assembled wind turbine apparatus, a power rectification module facilitating AC-DC conversion, and a suite of controllers facilitating maximum power point tracking (MPPT) and safety protocols, this solution is poised to address the exigencies of reliable and efficient power generation. Moreover, a power routing mechanism is envisaged to seamlessly transition to an alternative power source in the event of wind turbine malfunction. Augmenting operational transparency, a user interface is incorporated to furnish real-time data encompassing voltage, current, and power source statuses. Additionally, to bolster safety protocols, supplementary fusing mechanisms and emergency shutdown functionalities are meticulously integrated into the design paradigm.

The visual aid shows the components and their interconnections, which demonstrates the top-level design of the solution. It is shown in Figure 1.1.

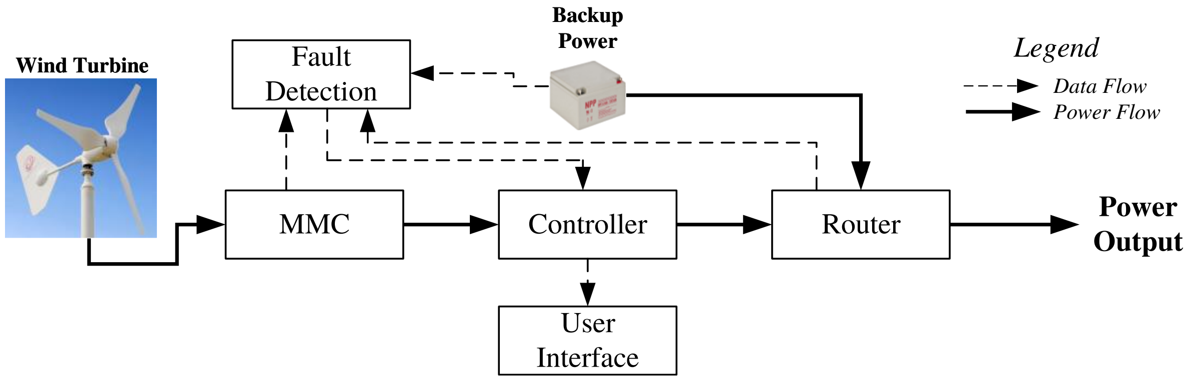

Figure 1.1 The visual aid of the proposed solution.

1.3 High-Level Requirements List

The following requirements should be satisfied to indicate a successful design of the wind power generating system integrated with a smart power routing function:

1. The design goal of the system requires the product to generate DC output from a wind turbine. The output voltage can be specified by the users through User Interface (UI). The system should be able to generate DC 10 V to 28 V DC output.
2. The output voltage and current ripple should not exceed ±10%.
3. The rated power of the system should reach 200 W and the maximum power tolerated by the system should be at least 300 W.
4. In consideration of safety issues, the power module and the control module should be well-isolated. All powerlines should be properly fused.

2 Design

2.1 System Overview

The design of the system can be broken into two major modules: the power transfer module, and the control module. The power transfer module consists of the turbine, an MMC-based converter, and a power router. They convert the mechanical energy of wind turbines into stable electrical energy. The control module is composed of the system controller, the Fault Detection Unit (FDU), and the User Interface (UI). They control the behaviors of the power transfer module and provide visual indications to the users. The block diagram of the system is shown in Figure 2.1.

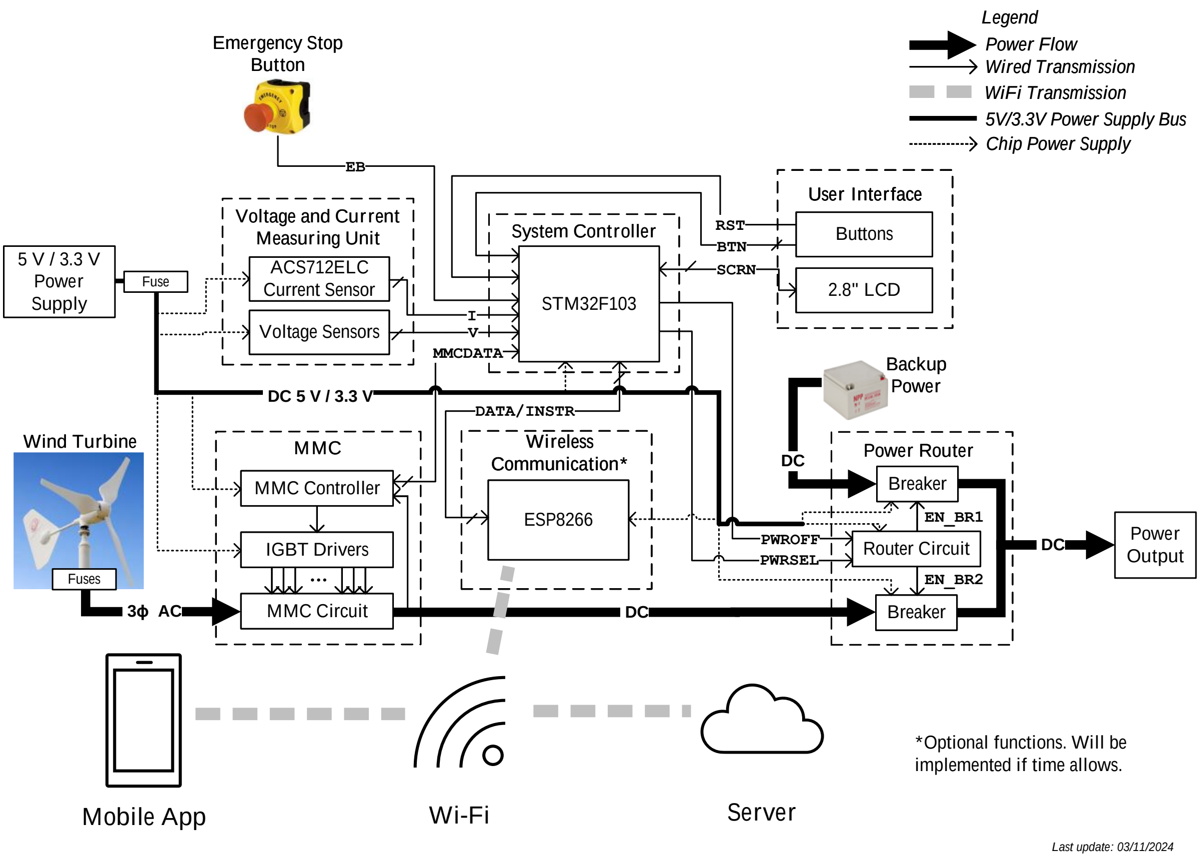

Figure 2.1 The block diagram of the system.

2.2 The Subsystems

2.2.1 Wind Turbine

The wind turbine is where wind power is collected. In this project, the team expects to use a pre-built three-phase generator available on the market with customized paddles. Table 2.1 shows the basic parameters of the chosen generator.

Table 2.1 Parameters of the purchased generator.

Item	Parameter
Rated Output Power	200 W
Rated Output Voltage	24 V
Rated Speed	950 rpm
Number of Paddles	8

2.2.2 MMC Converter

The MMC converter is designed to convert three-phase AC power generated by the turbine into stable DC power and provide support for MPPT. The converter is composed of several identical submodules built by IGBTs and capacitors. One of the most important advantages of applying MMC is the ease of maintenance, as the submodules connected in series are identical. The number of submodules applied to each branch is to be determined by further calculation and simulation.

A typical design of an MMC converter is shown in Figure 2.2, and the requirements for the MMC applied in this project are listed in Table 2.2. Note that the range of available input voltage should be subject to change with the actual performance measurement of the wind turbine.

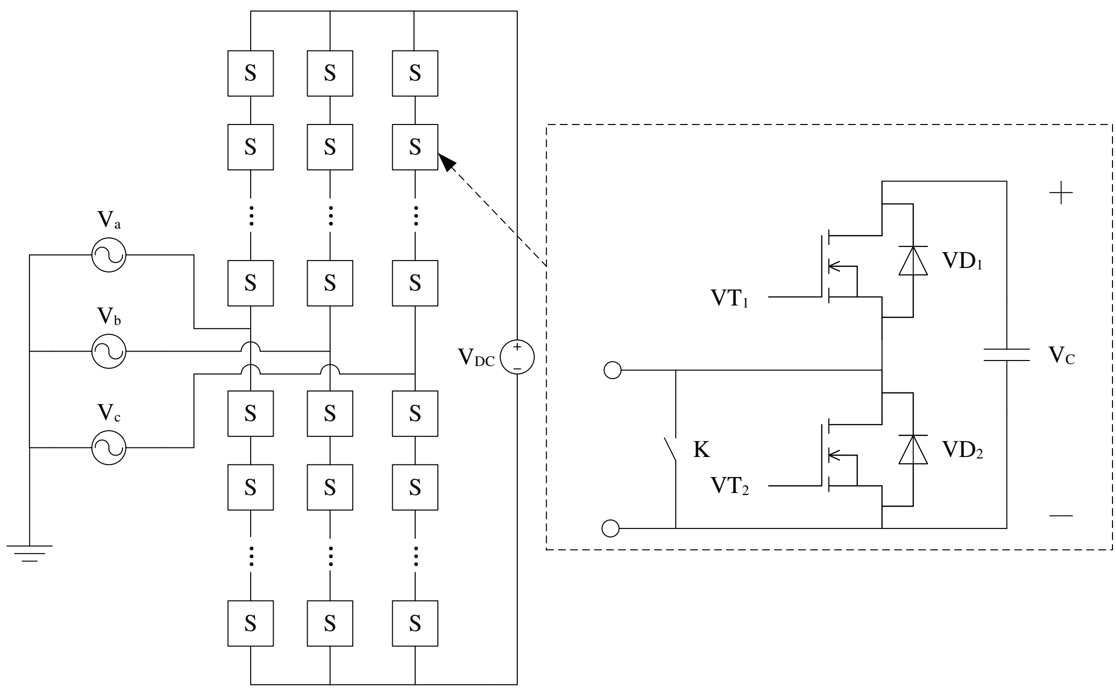

Figure 2.2 The circuit design of an MMC converter [2].

Table 2.2 Requirements for MMC

Item	Requirements
Input Voltage	To be determined after testing the turbine
Rated Output Voltage	Specified by the user through UI
Maximum Ripple	±10%
Rated Power Output	200 W
Maximum Power Output	300 W
Switching Frequency	10 kHz

2.2.3 Power Router

The power router can switch the output between backup power and turbine power according to the input control signal. The `PWRSEL` signal controls which power source is expected to be connected to the output, the backup source or the power output of the MMC converter. The `PWROFF` signal controls if the router should connect to any power source or cut the power off.

A diagram of router design is shown in Figure 2.3. The router circuit sends control signals to breakers according to the power source selection signal and power-off signal. It can be implemented using combinational logic. The breaker connects and disconnects a power source to the output according to the control signal.

Note that the breaker is implemented using a relay for isolation purposes, where a BJT/MOSFET is required to drive the relay as the output current of a typical gates chip is too small to drive the relay. For example, the SN7408 positive-and gate from Texas Instruments generates 16 mA maximum output current [3], but the G5NB-1A power relay from Omron requires 40 mA rated current for the coil [4]. Therefore, a BJT [5] or a MOSFET [4] should be connected to provide sufficient current.

The requirements for power router design are listed in Table 2.3.

Table 2.3 Requirements for The Power Router

Item	Requirements
Functionality	Route proper power source to output
Voltage Tolerance on Relay Contacts	>30 V
Current Tolerance Through Relay Contacts	>10 A
Special Requirement	Breakers should not be turned on at the same time

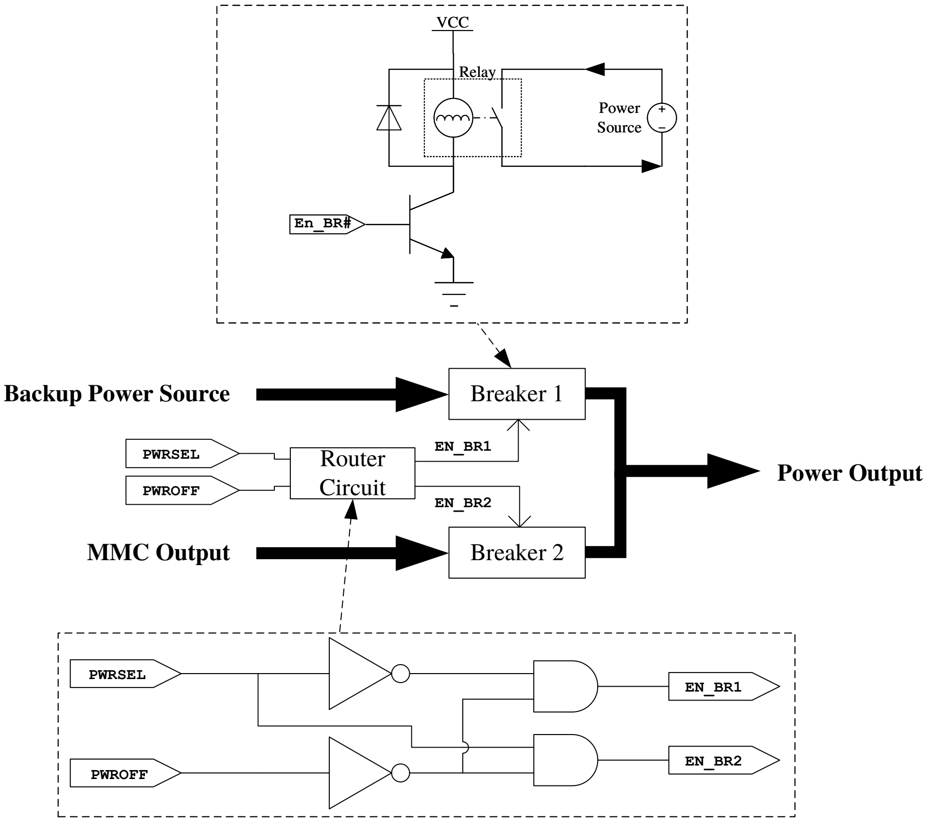

Figure 2.3 An example design of the power router with a proposed solution of the router circuit and breakers.

2.2.4 Backup Power

The backup power serves as an alternative for the users to obtain a stable power supply when the wind turbine fails under circumstances including extreme weather conditions. The team plans to serve a switching power supply connected to the utility power as the backup power source. Table 2.4 shows the requirements for a preferred backup power source.

Table 2.4 Requirements for Backup Power Source

Item	Requirement
Output Voltage	Specified by the user through UI
Error	±10%
Rated Output Power	250 W
Maximum Power Tolerance	>300 W

2.2.5 System Controller

The system controller controls the source connected to the output power, processes interactions between the users and the system, and provides fault detection.

Main Control Unit

The core of the controller is an MCU on a minimal system development board existing on the market, which reduces the workload of the development. Tentatively, the team plans to use an ALIENTEK STM32F103 development board (as is shown in Figure 2.4) with SRAM. The MCU is planned to be programmed with Real Time Operating System (RTOS) to multi-task operation, which allows the system to handle power calculation, routing control, user interface process and safety monitoring at the same time. A Message Queuing Telemetry Transport (MQTT) client will be integrated into the controller to provide wireless communication function that works in conjunction with an ATK-ESP8266 module, which will be discussed in §2.2.9.

Figure 2.5 shows the block diagram of the system controller, and Table 2.5 demonstrates the requirements for the system controller.

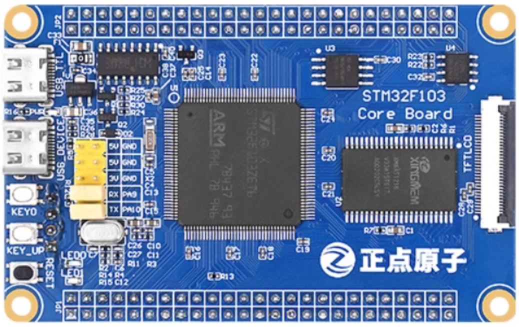

Figure 2.4 The ALIENTEK STM32F103 minimal system development board.

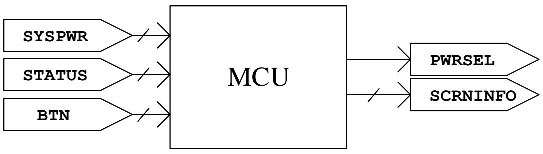

Figure 2.5 The block diagram of the system controller.

Table 2.5 Requirements for System Controller

Item	Requirement
Functionality: Power routing	To control the router to select the proper source of output
Functionality: UI Control	To process user interactions and indicate system status
Functionality: Wireless Communication	To control ATK-ESP8266 to transmit data

Fault Detection Unit

The Fault Detection Unit (FDU) is the key design to ensure the safety of the system. It calculates the real-time power of each power source and the output and cuts off the power output when the system fails. As a safety measure, the EB is connected to FDU output signals with combinational logic to provide manual power-off functionality. Though listed as a separate module, the FDU will be programmed on the same MCU with the system controller for better integration and efficiency.

Figure 2.6 demonstrates an example design of an FDU. The requirements of FDU design are listed in Table 2.6.

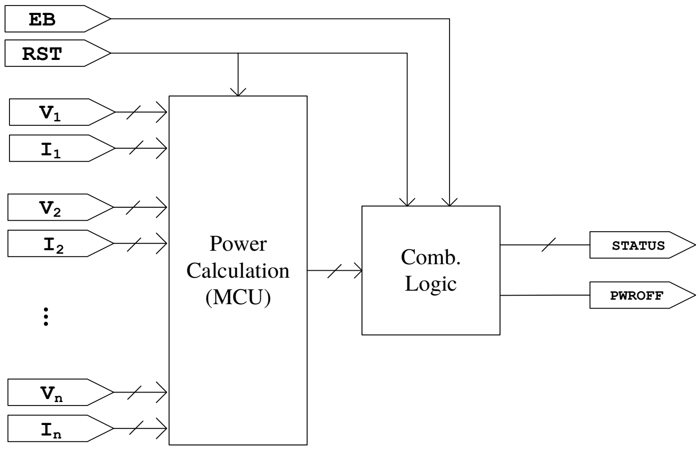

Figure 2.6 The block diagram of the FDU.

Table 2.6 Requirements for FDU

Item	Requirement
Range of Power Calculation	−500 W to 500 W
Accuracy	0.1 W
Error	<10%
Sampling Rate	>500 Hz

2.2.6 User Interface (UI)

The User Interface (UI) is designed to inform the user about the real-time status of the system and provide a control interface between the user and the system, including specifying output voltage. The source of output, the output power, output voltage and current, and turbine speed are displayed on an LCD screen. Figure 2.7 demonstrates an example design of a control panel, and Table 2.7 lists the requirements of the UI.

If the schedule allows, the team expects to provide an IoT interface with an ESP8266 module which allows the system to communicate with users' mobile clients through MQTT-based servers. This will be implemented if the schedule allows.

Table 2.7 Requirements for UI

Item	Requirements
LCD Refreshing Rate	>10 Hz
Contents Displayed	Status, output source, output power

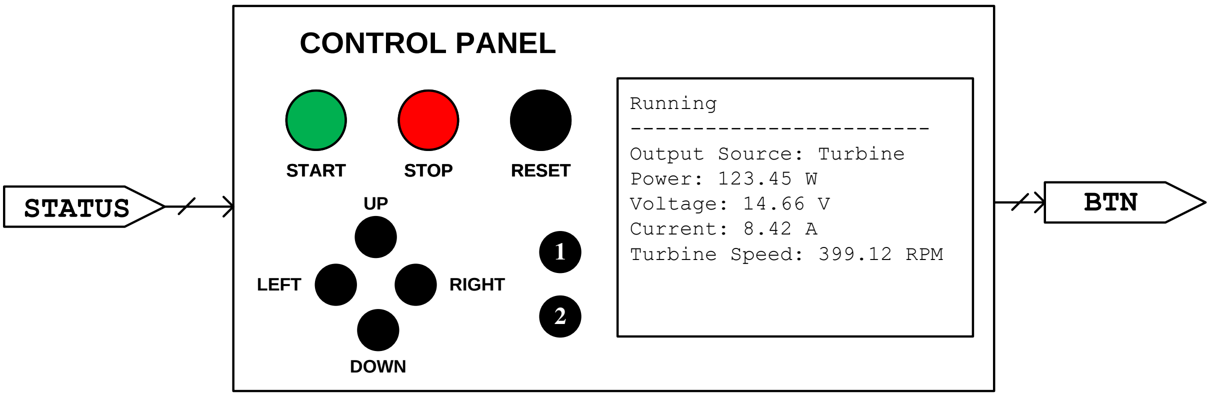

Figure 2.7 Design of user interface. Buttons labeled "left," "right", "up," "down", "1", and "2" are reserved for further UI change as menus might be introduced in the future to provide user customization.

2.2.7 Low Power Supply Module

All modules mentioned in the previous sections require 5 V power supply. Considering the time available for the project, this module is designed to use existing 9 V batteries with an ICW7805T2G power management chip, the latter of which produces stable 5 V output.

Figure 2.8 shows a typical 9 V battery, and Table 2.8 demonstrates the requirements for the low power supply module.

Figure 2.8 A typical 9 V battery.

Table 2.8 Requirements for Low Power Supply Module

Item	Requirement
Output Voltage	5 V±0.05 V and 3.3 V ±0.05 V
Maximum Current Tolerance	>500 mA

2.2.8 Voltage and Current Measuring Unit (VCMU)

The Voltage and Current Measuring Unit (VCMU) is designed to obtain real-time voltage and current of a power source, which can be accomplished by off-the-shelf chips. The block diagram of a VCMU is shown in Figure 2.9: the power flow goes through a hall effect-based current sensor, and an ADC converts the analog current measuring result into digital signals which can be understood by the MCU. A probe is applied to the power flow to get the voltage, and a voltage divider limits the measured voltage within the input range of the ADC. The ADC then converts analog measuring results into digital signals.

A blog post [6] mentions a voltage divider-based voltage sampling circuit that can be applied by this project.

The requirements of a successful VCMU design are shown in Table 2.9.

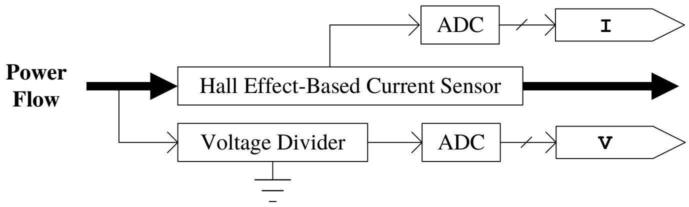

Figure 2.9 An example design of a VCMU.

Table 2.9 Requirements for VCMU

Item	Requirements
Range	DC −10 A to 10 A, −30 V to 30 V
Accuracy	0.1 A
Error	±10%
Protocol	I2C or SPI

2.2.9 Wireless Communication

The wireless communication module[1] is designed to allow users to monitor and control the system remotely. When under circumstances like extreme weather, users will be able to know about the status of the turbine and perform necessary actions without going outdoors.

The module will be implemented using an ATK-ESP8266 module which can connect to a Wi-Fi Acess Point (AP) through 2.4 GHz channel. The ATK-ESP8266 supports multiple wireless network standards including IEEE 802.11b/g/n. With a TCP/IP protocol stack integrated, the ATK-ESP8266 module can communicate with other devices through serial ports without any tricky configuration.

To provide low-power message transmission, the team plans to apply the MQTT protocol to the project. A mobile app is also planned to be created by using MIT App Inventor[2] to allow remote user interactions.

The requirements of the module are listed in Table 2.10.

Table 2.10 Requirements for Wireless Communication Module

Item	Requirement
Number of User Connections	>3
Supported Client OS	Android
Refresh Rate	>2 Hz

[1]Due to the tight schedule, this module might not be implemented in the final product.

[2]The MIT App Inventor is “an intuitive, visual programming environment that allows everyone –even children –to build fully functional apps for Android phones.”[7] It will simplify the development of the Android App.

2.3 Tolerance Analysis

The most important part of the project is the MMC-based power converter for AC/DC. Since the MMC has significant importance towards effective and reliable power conversion, as the crux of the project, its complexity and the precision required for its design and implementation pose significant challenges.

MMC must handle high voltages and currents while keeping output stable. However, achieving this stability requires precise control of parameters such as switching frequency, voltage level across capacitors and current on each arm. On the other hand, incorporating MMC into other system parts such as the wind turbine, control systems and power router also brings about some challenges that may ensure compatibility and smooth operation between them so that they can give an expected performance of the system. Besides, any deviation from the optimal scenario might have a chance to lead to efficiency loss, system instability, or even the whole system collapse.

2.3.1 Working States of MMC Submodules

Referring to [2], [8], a single submodule has three states: the ON state or *inserted* state the OFF state or *bypassed* state, and the *blocked* state, as are demonstrated in Figure 2.10. The submodule changes its working state with VT_1, VT_2, and K. The relationship is listed in Table tb:mmc-sub-states.

The ON State In this state, VT_1 is set to high and VT_2 to low, which turns the upper IGBT on and lower IGBT off, allowing current to flow through the capacitor. The capacitor is charged or discharged with the change of the terminal voltage of the submodule, i.e. $V_S = V_C$.

The OFF State In this state, VT_1 is set to low and VT_2 to high. The capacitor is bypassed by this IGBT configuration, and the voltage across the submodule becomes $V_S = 0$.

The *blocked* State This is a special state where the switch is closed, which allows the submodule to be fully disconnected from the converter. This allows the converter to disable certain submodules when they are not operable, which adds to the robustness of the system.

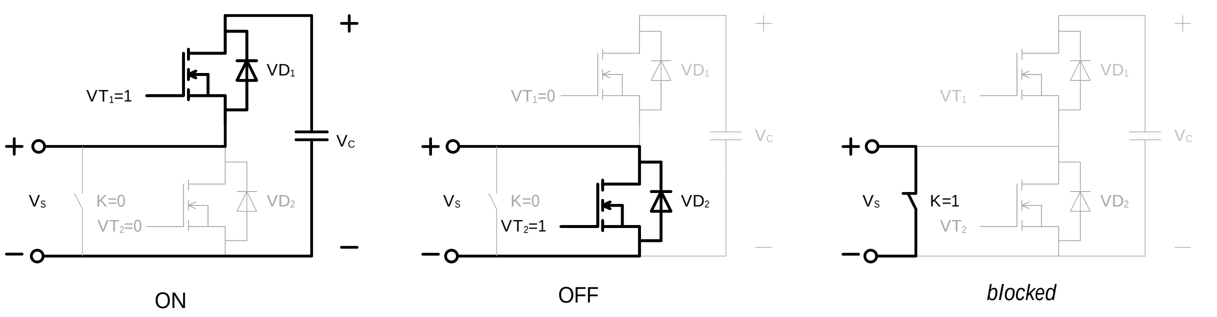

Figure 2.10 Different working states of a single MMC submodule.

Table 2.11 Working States of A Submodule with Different VT_1 and VT_2

State	VT_1	VT_2	K	V_{out}
*	0	0	0	*
OFF	0	1	0	0
ON	1	0	0	V_C
*	1	1	0	0
blocked	*	*	1	V_C

2.3.2 Control Strategy of MMC

Based on the states discussed in §2.3.1, the MMC is able to approximate DC voltage output by controlling the number of submodules inserted into the system. One of the simplest control strategies is "Nearest Level Approximation Modulation", where the system adjusts the number of submodules inserted to align the system output voltage with the desired output.

To show how the MMC is going to produce stable DC output, let's take a look at a single-phase dual-branch MMC circuit. Figure 2.11(a) demonstrates a single-phase MMC topology. The sinusoidal AC power source, $v_{ac}(t)$, is connected to a single-phase MMC AC-DC converter. The circuit produces an approximation, $v_{DC}(t)$, to the desired DC voltage V_{DC}. The goal of the circuit is to keep $v_{DC}(t)$ close to V_{DC} by controlling the number of submodules inserted on each branch, N.

Recall that the voltage across a capacitor, $v_c(t)$, satisfies the differential equation

$$\left[\frac{\mathrm{d}v_c(t)}{\mathrm{d}t}\right] C = i_C(t) \tag{2.1}$$

where $i_C(t)$ is the current flowing through the capacitor. This indicates that the voltage across the capacitor will not change suddenly, as the differentiation term requires $v_C(t)$ to be differentiable. With this in mind, let's assume $v_C(t)$ almost remains constant and the qualitative analysis should explain the principle of the MMC control strategy:

1. When $v_{ac}(t)$ rises, if the number of submodules inserted does not change, v_{DC} also rises. To suppress the trend, the number of submodules inserted in the upper branch should be reduced, and the number in the lower branch should increase.
2. When $v_{ac}(t)$ falls, to suppress the trend, the number of submodules inserted in the upper branch should be increased and that to the lower branch should be reduced.
3. To keep v_{DC} almost constant, the total number of submodules inserted on both branches should remain constant.

The waveform of output voltage v_{DC} under the step-change strategy illustrated above should look like Figure 2.11.

While the qualitative analysis may lack accuracy in illustrating the working principles, it gives an overview of the feasibility of the converter designed with MMC. For quantitative analysis, [2], [8]–[10] have mentioned the feasibility of MMC in different ways with both mathematical proof and simulation results. All of them support the feasibility of integrating an MMC-based converter into our wind power generating and routing system.

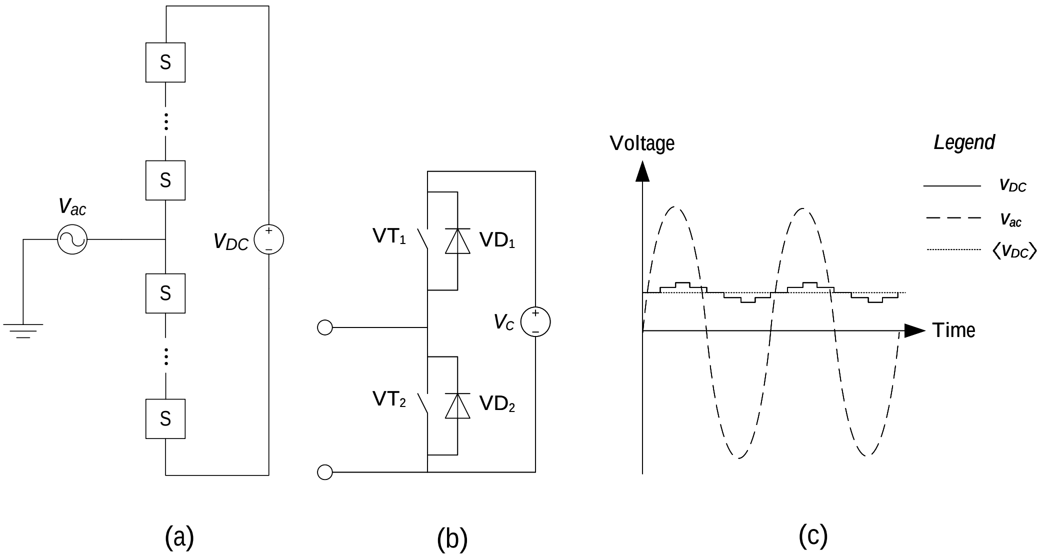

Figure 2.11 (a) The single-phase MMC topology, (b) the equivalent circuit of an MMC submodule, and (c) an approximation of the DC output V_{DC} waveform.

2.3.3 MMC Design Workflow

To ascertain that our project's MMC section operates effectively, we will conduct simulations and modeling under various operating conditions as part of project feasibility tests to understand how the bidirectional converter behaves. Similarly, we will also conduct different test cases and validation to ensure that the converter meets all anticipated performance standards. Leveraging our expertise in power electronics and control systems is also a guarantee to the final success. In addition, their use will enable us to design and implement advanced control algorithms that are adaptable to the constantly changing nature of systems leading to the MMC running at its highest efficiency while maintaining the stability and reliability of the system.

3 Ethics and Safety

3.1 Safety

Safety is always the top priority when it comes to the design of physical systems. As this project involves electrical and mechanical parts, the safety of the surroundings of the system is important. To ensure safety within the development process and the throughout lifecycle of the product, it is vital to keep the following requirements satisfied:

1. Keep clear of the wind turbine whenever it is unlocked and can rotate freely to avoid any people being hurt by the rotating turbine.
2. Keep the circuit well enclosed within water-resistant containers whenever the generator system is applied in any outdoor environment.
3. All power transmission lines within the generator system should be properly fused to avoid fire triggered by overheat.
4. All subsystems related to rechargeable battery use should comply with "Safe Practice for Lead Acid and Lithium Batteries" [11], and the customized battery charger should comply with "Household and similar electrical appliances – Safety – Particular requirements for battery chargers" (GB 4706.18-2014) [12].
5. All wires and devices that have current and/or voltage exceeding the limit set by China National Standard "Extra-low voltage (ELV) – Limit values" (GB/T 3805-2008) [13] should be kept unreachable by the surroundings unless they are unconnected to power.
6. The generator system should comply with the following China National Standards:
    (a) "Household And Similar Electrical Appliances – Safety – Part 1: General Requirements" (GB 4706-2005) [14].
    (b) "Generator of Small Wind Turbines – Part 1: Technical Condition" (GB/T 10760.1-2017) [15].

3.2 Ethics

Ethical considerations are vital to a successful product design. The development of the project should strictly follow "IEEE Code of Ethics" [16], and the team will devote themselves to upholding integrity, responsibility, and professionalism. The product should not convey discrimination towards any person or group, and be kept from injuring any surroundings.

In detail, the following requirements should be remembered during and after the senior design project:

1. The "IEEE Code of Ethics" [16] especially mentions that the engineers should "hold paramount, the safety, health, and welfare of the public," which is vital to the success of this project. The safety and health of any person or animal involved in this project should be ensured. For this project, the turbine should be kept from injuring any animals like birds that fly by, and any people around.

Careful check is necessary before unlocking the turbine and starting the system to ensure people around are aware of the rotating paddles and animals are away from the testing site.

2. Academic integrity is important to this project. During the development, any work done by another person or team that is applied to this project should be cited properly in any documents written for this course. The team should make sure the project submitted is their original work, and to "credit properly the contributions of others" [16] when presenting their work in either written form or oral form.
3. Teamwork matters. The team agrees that they will "seek, accept, and offer honest criticism of technical work" [16] to each other. Everyone in the team should be "treated fairly and with respect" [16]. The team should not discriminate against anyone either in or out of the team.
4. Compliance. The development process and the product itself should comply with relevant laws and national standards mentioned in §3.1. The purchase of any materials needed for the project should be properly recorded and archived for further investigation of expenditures.

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