# 3 Preliminary Design and Results

In this section, we will talk about the design we came up with in the very beginning and talk about what worked, what didn’t work, how we tested it, and how we came up with this initial idea in the first place. What our initial goal was and how it panned out.

Our goal was to

* Design a way to split single phase to three phase using some concepts from an old project as inspiration.
* Design a way to automatically adjust phase angles in real time as the input frequency changes.
* Design a power amplifier capable of driving very low impedance loads. This amplifier must also have low output distortion.
* Combine all of the above into one unified system.

Write anything else here that would introduce the sections below and a transition sentence that lets the reader know that the next section is single to three-phase without saying that.

## 3.1 Single Phase to Three Phase

* Two circuits one that can shift a sine wave between 0° and 180°, and the other can shift between 0° and -180°
* I used what I had on hand.
* Using prior experience in combination with some online and textbook research
* The phase splitting worked however it created too much output noise
* I tested this part by using a function generator to output a 2v 60Hz sine wave and measuring the three output waveforms using my 4 Channel Oscilloscope. The scope can compute the phase angles.
* I only tested this part on its own
* The three-phase output connects to the power amplifier

## 3.2 Three Phase Data Acquisition

* It measure and controls the phase angles of the 3 phases. It will tune the potentiometers in Single Phase to Three Phase circuits based on frequency to maintain an angle of 120° between each phase
* The Raspberry Pi is an easy to program platform with lots of compute power, the MCP3008 ADC has a fast sampling rate, has multiple channels, and can compare channels on the chip for full ac input.
* I have a lot of experience with data acquisition using microcontrollers.
* The design failed because the operating system on Raspberry Pi is Linux based which is not a real time operating system. Because of this the measurements had poor precision and accuracy.
* I tested the data acquisition system by connected a function generator outputting a 2v 60Hz sine wave to the MCP3008 adc which is connected to the Raspberry PI.
* The measured input would then be used to control the Digital Potentiometer to adjust the phase angle of the single phase to three-phase circuit.

## 3.3 Power Amplification

* The Power Amplification stage uses the three-phase output as inputs so that its output can drive low impedance loads. This is necessary because the op-amp’s used can only output a maximum of 500mW. For example if the phase 1 has a amplitude of 10 volts connected to a 10 ohm load Since P=V2/R the resulting power is 10W which is 20x what the op-amp can deliver on its own. The power amplifier stage takes the input power and multiplies it so it can maintain the same voltage regardless of the load impedance.
* I choose the components based on their power rating and cost.
* I do a lot of electronics projects my free time so this is nothing new.
* The LM833n op-amp used in the design to drive the class B bjt based power amplifier, worked but due to its internal construction it created a lot of output noise.
* The Power Amplification Stage was tested using the three-phase output of the phase shifting circuit. The output and input were connected to my oscilloscope so I could compare them.

## 3.4 Preliminary Results

The advanced phase splitting circuit worked perfectly with a regular potentiometer but was incompatible with a digital potentiometer. The data acquisition and control system was not precise, accurate, or fast enough. The power amplification stage worked but the op-amp used needed to be replaced with one that has a different internal design.

# 4 Final Design and Results

In this section, we will talk about the final design we came up with and talk about what worked, what didn’t work, how we tested it, and our solution to what didn’t work.

* The advanced phase splitting circuit worked very well
* The LM358 op-amp in the phase splitting circuit was replace with an LM833n.
* The digital potentiometer didn’t work so a custom electromechanical potentiometer had to be designed and fabricated.
* The control system had to be redesigned from the ground up
* Converting a sine wave to a digital waveform was harder than expected; numerous revisions were made.
* Low speed TTL based chips were replaced with high speed CMOS based chips to reduce the propagation delay.

Write anything else here that would introduce the sections below and a transition sentence that lets the reader know that the next section is single to three phase without saying that.

## 4.1 Emitter Follower Buffer

In the final design, emitter follower buffers were added between the input sine wave from DC to AC conversion and the inputs to the single-phase to three-phase circuit. These buffers were used to ensure that there is no interference between each phase. The design uses a 2n2222a BJT transistor, a 1n5819 Schottky diode, a capacitor and some resistors. The Schottky diode is connected from the base to the collector of the BJT, doing this ensures that the BJT will not go into saturation thus removing the need to bias the transistor. The parts were chosen based on what I had on hand. The design was simulated first using TINA and then constructed and tested with a function generator and oscilloscope.

## 4.2 Single Phase to Three Phase

The final design of the single-phase to three-phase system uses the advanced phase splitter design with a custom motorized potentiometer in place of the digital one in the preliminary design. The LM358n op-amp was replaced with a LM833n op-amp because it has a high slew rate, high operating supply voltage, and can output up to 500mW. This combination results in a output with little to no distortion. All the designs were simulated in TINA then tested using an oscilloscope

### 4.2.1 Motorized Potentiometer

The motorized potentiometer design came about when the digital one didn’t work with an ac waveform and found out no such product exists. The design uses a readily available 12V dc motor with worm drive, a 10 turn 50k ohm rotary potentiometer, a 6mm shaft coupler, and a motor holder. The chosen worm drive is spec’d at 6 rpm and has a 6mm shaft, the potentiometer was chosen because it can be finely adjusted and has a 6.3mm shaft. The shaft coupler was chosen because it fit on the output shaft of the worm drive and with some slight modification it fit on the potentiometer shaft as well. The motor holder is a custom 3D printed part that was modelled in Autodesk Inventor 2020. An LM298n H-Bridge module was used to drive the motor, it was chosen because it’s cheap and easy to use.

## 4.4 Three Phase Data Acquisition and Control System

The final design of the data acquisition and control system uses the STM32F446RE microcontroller programmed with MBED-OS. The STM32F446RE board was chosen because I have used it in several other projects that require data acquisition and control. MBED was chosen because it is an open-source platform that supports a real time operating system (RTOS). This combination was chosen because data acquisition system needs to be able to measure frequency and phase angles with high precision and accuracy. The control system needs to be capable of fast transient response with low steady state error, while also being able to provide feedback to the user. To measure the frequency as well as phase angles the sine wave outputs need to be converted a digital signal. Once converted to a digital signal we can measure the frequency by measuring the time between the rising and falling edges of phase 1 then doubling that value to obtain the period, and thus the frequency. To measure the phase angles, we needed to know the time delay between the rising edge of one phase with respect to another. The solution was to XOR the phases, doing this results in a signal were measuring the time between the rising and falling edges will give the time delay between two phases. By knowing the frequency and time delay the phase angle can be computed. This computation is done for phases 1-2, 1-3, and 2-3. The control system uses the measured phase angles and controls the two H-Bridge Drivers on the motorized potentiometers; the motors have three states rotate left, rotate right, and off. The controller takes the measured phase angle and checks if the measured is withing .5% of the setpoint (in this case 120°). It will adjust up or down accordingly if not within the .5% other wise it will turn the motors off. This system will update every 100uS and will send the frequency, current phase angles to a computer via USB.

### 4.4.1 Sine Wave to Digital Signal Conversion

Since the microcontroller and logic gate can only using digital signals each phase needed to have a corresponding digital equivalent. This was done in two steps with the first being converting the sine wave to a square wave at the crossover points then level shifting said square wave resulting in a usable logic signal. The parts used for this are LM833n op-amps, 1n5819 Schottky diodes and some resistors. The op-amps are cheap, and I had a lot on hand. The Schottky diodes were chosen for their low forward voltage and fast recovery time.

## 4.6 Power Amplification

The final design of the power amplifier is based on a Class B dual supply amplifier, but an op-amp is added to provide feedback to remover the crossover distortion that normally occurs with this design. The LM833n op-amp used in the preliminary design was replaced with a LM358. Other components used were the following TIP41C and TIP31C NPN Power BJT’s in a Darlington config, as well as the complementary TIP42C and TIP31C PNP Power BJT’s also in a Darlington config. These were chosen for their low cost and high-power capabilities. When put together the resulting power amplifier has excellent power gain, and very little output distortion

## 4.4 Final Results

All the parts came together to meet and exceed the set constraints and goals.