Sinusoidal PWM Generation for 3 Phase Inverter and RPM Measurement using Hercules TMS570LC43xx Launchpad

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Abstract:- This project focuses on implementing a 3 phase Sinusoidal PWM generation using the Hercules TMS570LC43xx Launchpad Development Kit (Launchpad). The primary objective is to generate synchronized Sinusoidal nature PWM signals using the onboard High-End Timer (HET) and Enhanced Pulse Width Modulation (ePWM) module, which can be given to the Inverter for conversion of Direct current (DC) power into Alternating current (AC) power. This conversion is essential in various applications where AC power is required but the power source provides DC power. It is used in Solar photovoltaic (PV) systems and other renewable energy installations. These systems generate power suitable for powering household appliances or feeding into the electrical grid. It is also used in electric vehicles (EVs) to drive the electric motor with variable speed.

For verification of the wave nature, we have used an external lowpass filter (LPF) to transform the dynamic PWM signals into sinusoidal waveforms, ensuring compatibility with various applications like Inverters which can be further used in equipment and machinery such as Brushless DC motors, pumps and compressors. With the addon functionality to control the signal's frequency which will be given to the Inverter to control the speed of the motor. Additionally, the project incorporates RPM measurement of the motor using an optical encoder setup interfaced with the Enhanced Quadrature Encoder Pulse (eQEP) module on the Launchpad. This feature enables accurate measurement of rotational speeds, position and Revolution per minute (RPM), enhancing the functionality of the system in real world applications like the speed of conveyor belts and other automated transport systems.

Through successful implementation, this project demonstrates wide control for the Inverter, achieving reliable synchronized 3 phase signals with its variable speed having 120-degree phase shift signals alongside precise RPM measurement. The project highlights the Launchpad's capabilities in handling complex signal processing tasks essential for modern power electronics applications. Looking forward, this project establishes a foundation for future enhancements and innovations in power electronics.

Keywords:- *Hercules, Inverter, SPMW, eQEP, RPM.*

I. INTRODUCTION

Inverters play an important role in modern power electronics, enabling the conversion of DC power into AC power across various applications. This project focuses on using the capabilities of the Launchpad to design and implement a 3 phase SPWM crucial for driving Inverters that convert DC sources, such as photovoltaic (PV) arrays, wind turbines or batteries into AC power used in applications such as renewable energy system suitable for powering household appliances or feeding into the electrical grid. The applications of 3 phase Inverters are widespread in numerous industries. Uninterruptible Power Supplies (UPS) provide backup power during mains power failures. The UPS typically stores DC power in batteries as a backup source in emergency which the inverter then converts to AC power to keep critical equipment running. In EV the conversion helps to drive the electric motor.

Industrial applications heavily rely on 3 phase Inverters for speed control of electric motors and compressors. Techniques like SPWM with a 120-degree phase shift effectively modulate the amplitude of the AC waveform. This modulation enables smooth control ensuring optimal performance across varying loads and operational conditions. This project showcases the feasibility of using the Launchpad for complex signal generation tasks with accurate frequency and pulse width. Demonstrating precise RPM measurement and synchronized 3 phase output. This project lays a foundation for advancements in power electronics, especially in village areas where the power lines have not yet been installed or are not very consistent.

II. ePWM MODULE

The ePWM module integrated into the Launchpad is a feature designed for PWM signal generation with user control parameters like time period, frequency, dead time delay, and interrupt. Unlike basic PWM generation in simple boards like TM4 TIVA C, the ePWM module in Launchpad offers enhanced functionalities including dead-time insertion, Clock Prescale, Trip Zone, and Interrupt.

In practical applications, the ePWM module finds uses in motor drivers facilitating precise adjustment of motor speed by varying the width of the pulses and also in power Inverters. Moreover, in Switch Mode Power Supply (SMPS)

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used in modern Computers and PC, it regulates the constant output voltage level with high accuracy, ensuring stability and efficiency with a greater life span as compared to the linear power supply. The average power using the SMPS is controlled using the PWM signal with close loop feedback to provide a constant power even after fluctuations.

➢ *Time base Submodule*

Each ePWM module has its Time base (TB) submodule that determines all of the event timing such as the TB period for the ePWM module. The builtin module allows the TB of multiple ePWM modules to work together as a single system or as an individual system. It is used to set the PWM period or frequency of each PWM signal and also maintains a phase relationship with other PWM signals. The TB counter can have 3 modes namely count-up, count-down, or count-up-and-down mode which are used for different conditions having their own advantages.

The count-up mode has been selected for this operation for better handling of the signal. In this mode, the time-base counter starts from zero and increments until it reaches the value in the period register TBPRD. When the period value is reached, the TB counter resets to zero and begins to increment once again. With the proper value of this period, we can keep the count for each cycle helping in accurate time seconds of delay. TBPRD is used to set the desired period of the PWM based on the formula given below.

$$PWM\ freq = \frac{1}{(\text{TBPRD}+1)\times TBCLK} \tag{1}$$

$$TBPRD = \frac{\text{TBCLK freq}}{PWM\ freq} - 1 \tag{2}$$

For Pulses of 5khz, the value of TBPRD will be

$$TBPRD = \frac{75\text{ MHz}}{5\ MHz} - 1 = 14999 \tag{3}$$

14999 is the period value set here, which determines how often the PWM signal repeats. This value will give an accurate 5KHz frequency at the output which can be seen in figure 1.

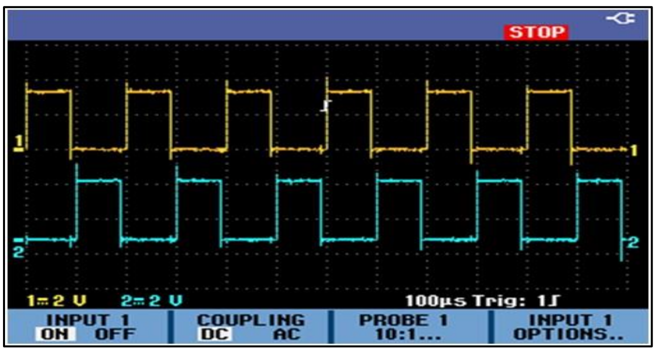

Fig 1 5kHz PWM signal using ePWM module.

➢ *Counter Compare Submodule*

The counter-compare (CC) submodule takes TB counter value as input which is compared to the counter-compare A (CMPA) and counter compare B (CMPB) registers. When the time base counter is equal to one of the compare registers, the CC unit generates a desired change in the pulses such as switching the level to low or high. CMPA and CMPB are individual registers for comparing the signals values. For up-count mode, each event occurs only once per cycle. We can calculate the value of counter period CMPA and CMPB based on the TBPRD value. For the 50% fixed duty cycle, we can calculate using the formula below which can be observed in Figure 1.

$$CMPA = CMPB = \text{TBPRD} \times \text{DutyCycle} \tag{4}$$

$$CMPA = CMPB = \frac{14999 \times 50}{100} = 7499 \tag{5}$$

➢ *Dead Band Submodule*

The Dead-Band submodule (DB) is used to prevent shoot-through currents in the circuit where two switching devices (like MOSFETs or IGBTs) control the flow of current through a load. In PWM systems, especially those controlling high-power devices, simultaneous switching of both switches can create a short circuit across the power supply, leading to over currents causing damage to the circuit or power supply and potential device failure.

The DB submodule introduces a small-time delay between turning off one switch and turning on the other. This delay, known as the dead time delay, ensures that both switches are never conducting simultaneously causing the short circuit. It effectively prevents shoot-through currents by allowing enough time for the current through one switch to fully decay or become zero before the other switch turns on. Once the first switch is turned off fully it will start the timer, after that delay of a few microseconds it will switch on another switch. The dead time delay can be set using the given equation below.

$$DBFED = \frac{Falling\ edge\ delay\ period}{TBCLK\ period} \tag{6}$$

$$DBRED = \frac{Raising\ edge\ delay\ period}{TBCLK\ period} \tag{7}$$

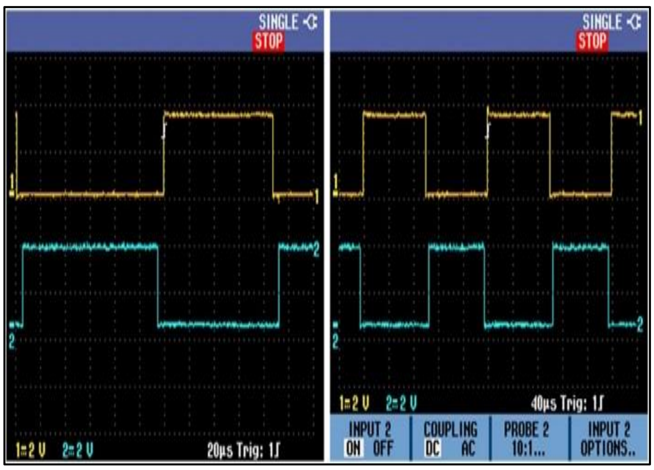

Fig 2 Dead Time Delay of 5 µs

To have a rising edge delay (RED) and falling edge delay (FED) of 5 µs we can find the values using the below

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formula which can be observed in Figure 2.

$$DBFED = DBRED = \frac{5 \times 10{-}6\ s}{13.33 \times 10{-}9\ s} \tag{8}$$

$$DBFED = DBRED = 375$$

- *Trip Zone Submodule*

The Trip zone (TZ) submodule is designed to monitor and respond to fault conditions during the process. It enhances the safety of PWM-controlled applications by detecting and reacting to various fault scenarios effectively. The TZ submodule is configured to monitor several inputs, typically up to six individual fault or trip signals labeled as TZ1 to TZ6. TZ1 and TZ2 is been used with external General Purpose Input Output (GPIO) pins for external interrupt for detection of failure.

When a fault condition is detected or the signal to the GPIO pin is logic high (3.3V), the TZ submodule triggers a response within the ePWM module to act according to the parameter. We have implemented 2 types of trips Cycle by Cycle and One-shot trip. Cycle by Cycle is used when we have to disable the module for some of the cycles or for some time until the input GPIO is grounded. Once the interrupt input is grounded or goes logic low then the ePWM will start to function as normal.

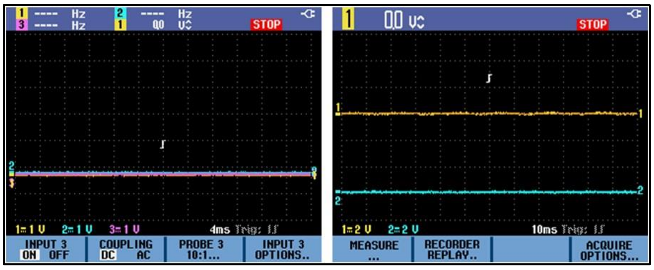

Fig 3 ePWM Disabled using One Shot Trip and Cycle by Cycle Trip

When the one-shot signal is high then the ePWM module will be disabled and will not be enabled until the board has an external reset. It Protects against overvoltage or short circuit conditions. The support for cycle-by-cycle tripping is for current limiting operation whereas the support for the one-shot trip is for major short circuits or over-current conditions and the same can be observed in Figure 3.

- *Sinusoidal PWM*

Sinusoidal PWM (SPWM) is a technique used to replicate a sine wave using PWM signals, commonly used in applications requiring smooth, sinusoidal nature. Asymmetric PWM can be achieved with the help of dynamic compare value CMPA/CMPB on TBPRD. By modulation or alternating the compare value from 0 to 2π we can achieve 0-100% PWM duty cycle. The formula for the dynamically changing duty cycle can be given as the equation below.

$$\mathrm{PWM}(\theta) = (\sin(\theta) + 1) \times 50\% \tag{9}$$

Here, θ represents the phase angle, which typically varies from 0 to 2π radians corresponding to one full 3 cycle of the sinusoidal waveform. As the value of sin(θ) goes from (-1, 1), offsetting the lower level by a value of +1 will shift the ground level and then multiplying it with 50% will enlarge the range to (0, 100) hence improving the resolution or minimum changes in only positive values. In Figure 4 we can observe the PWM cycles changing its duty cycle asymmetrically.

Fig 4 Sinusoidal Pulse Width Modulated Signals

- *RC Filter for PWM to Sinusoidal Conversion*

Converting a PWM signal to a sinusoidal waveform using a Resistor and Capacitor low pass filter (LPF) is a common technique in our application we can verify the nature of the PWM signal by using an RC low pass filter to see if the desired waveform is generated. A smooth and continuous waveform is desired to be observed after the filtering of the signal. The PWM signal can be directly observed on the oscilloscope but the nature will be unknown as Sine and Triangular PWM will have almost identical signals and will not be able to differentiate visually. To verify the nature the only way is to pass it through the low pass filter to fully attenuate the high-frequency carrier component and only get the desired signal. The duty cycle determines the average voltage level throughout the sinusoidal wave. It is a simple circuit consisting of a resistor and a capacitor connected in series. The output is taken from the capacitor as it has the advantage of allowing the AC signal to be grounded and block all the DC components thus dropping all the DC components across it.

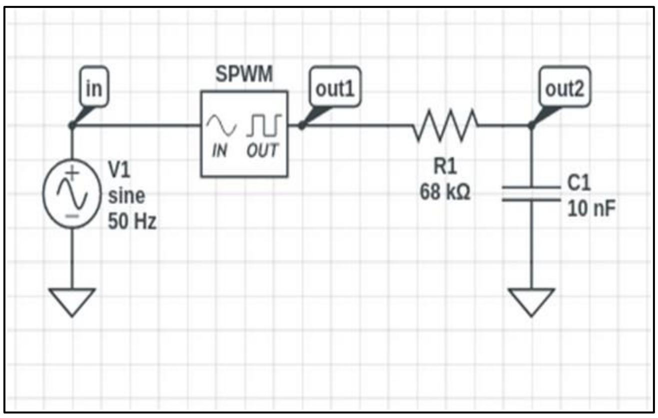

Fig 5 Circuit Design for RC low Pass Filter

The cutoff frequency Fc of the RC low pass filter determines how effectively it can filter out the PWM switching frequency and recreate the modulating frequency. In our application, the PWM or carrier frequency is set as 5

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kHz and the fundamental frequency is 50 Hz suitable for the Inverters. The equation for the desired cutoff frequency Fc is given as.

$$Fc = \frac{1}{2 \times \Pi \times R \times C} \tag{10}$$

Where, R = 68 KΩ and C = 0.01 µF

$$Fc = \frac{1}{2 \times \Pi \times 68\ K\Omega \times 0.01\ \mu F} = 234.05\ Hz \tag{11}$$

The RC low pass filter with a cutoff frequency Fc equal to 234.05 Hz which will effectively attenuate frequencies above 234.0.5 Hz and pass frequencies below this cutoff. The carrier frequency of 5 kHz is significantly higher than Fc, so it will be rejected. The fundamental signal frequency of 50 Hz is much lower than Fc, so it will pass through the filter. By choosing appropriate values of R and C for the RC low pass filter we can adjust the value of Fc range

SPWM only introduces frequency components primarily at the carrier frequency and its fundamental frequency. It only introduces components at specific frequencies (carrier and fundamental), making it suitable for Fourier series analysis and effective filtering with a low pass filter. This differentiation and selective attenuation of higher frequencies facilitate the conversion of SPWM back to a sine wave. This technique is widely used in communication systems, signal processing, and various electronics applications. The same can be verified below in the waveforms.

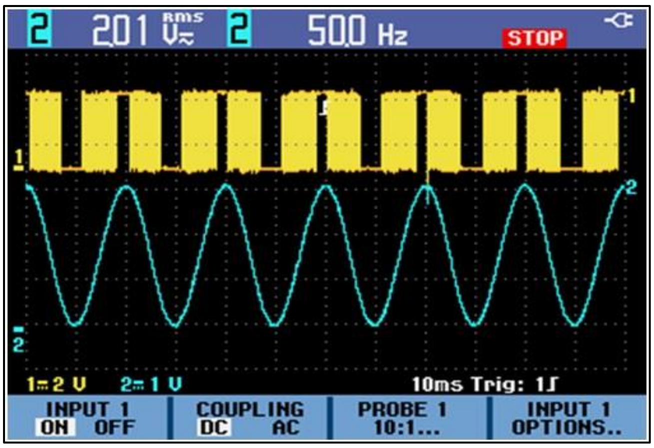

Fig 6 PWM to Sinusoidal using RC Filter

III. INVERTER GATE SIGNAL GENERATION

PWM signal having a sinusoidal symmetry can be used as an input to the Inverters. The process involves generating a high-frequency waveform (carrier signal) using Launchpad. By changing the instantaneous value of this sinusoidal reference signal CMPA with the carrier signal, the microcontroller adjusts the width of the PWM pulses. The width of each pulse corresponds to the amplitude of the sinusoidal reference signal at that moment, to replicate the nature of the desired Sinusoidal waveform. With proper timing and the use of enhanced functionality, we can get a controlled output suitable for one leg of the Inverter.

For our application, we generate a high-frequency carrier signal, typically at 5 KHz using the ePWM module. Then a sinusoidal reference waveform, representing a 50 Hz AC voltage, is defined using the sine function. The ePWM module dynamically adjusts the width of PWM pulses. The resulting PWM signal will have the desired nature similar to Sinusoidal at 50 Hz. The same signal can be observed below in the waveform below confirming the effectiveness of Launchpad in producing the desired SPWM output.

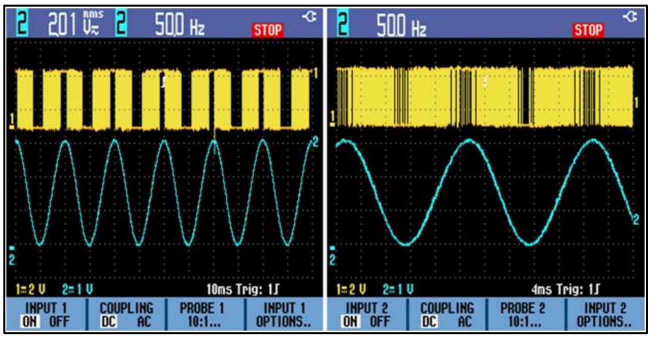

Fig. 7 PWM Generation having Sine Nature

This SPWM signal can be given to a gate driver core to generate gate signals for the Inverter switches.

➢ *Three Phase Inverter Signals*

Modern Inverters employ advanced control techniques to generate three-phase AC voltage waveforms. This involves generating 3 separate AC signals, each phase shifted by 120 degrees relative to the others. Each phase of the Inverter is controlled independently using PWM techniques. Insulated Gate Bipolar Transistors (IGBT) are semiconductor devices capable of handling high currents and voltages.

They are used as switches in Inverters to control the flow of current from the DC input to the AC output. IGBTs switch at high frequencies typically in the KHz range. This switching action allows precise control over the amplitude and frequency of the AC output waveform. IGBTs are chosen for their efficiency in switching and low conduction losses, ensuring that the Inverter operates with minimal energy loss and heat generation. In industrial applications, 3 phase signal is used for Regulating speed in electric motors. The 3 phase signals can be observed in the figure 8.

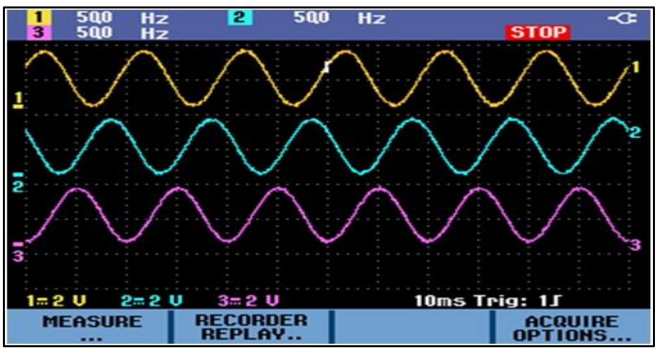

Fig 8 3 Phase Sinusoidal Signals having Identical Parameters.

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A three-phase AC system consists of three sinusoidal voltage waveforms, each offset from the other by 120 degrees in phase. These waveforms are typically labelled as phases A, B, and C. Phase B leads Phase A by 120 degrees. Phase C leads Phase B by another 120 degrees, completing the full 360-degree cycle. 3 phase signals are more efficient than single-phase signal for transmitting and distributing electricity over long distances and for powering large industrial loads. The 120-degree phase shift ensures that the power delivery is smooth and continuous, improving overall system stability. In induction motors, the windings are designed to correspond to the three phases of the AC supply.

The phase shift between the winding's creates a rotating magnetic field, which induces rotor movement and enables the motor to run smoothly and efficiently. It is essential for generating balanced AC output, ensuring that the load receives consistent and reliable power. Each signals have identical amplitude and frequency. The timing of PWM signals across the 3 phases must be precisely controlled to maintain the desired phase relationship and ensure efficient operation. The 120-degree phase shift can be seen in Figure 9.

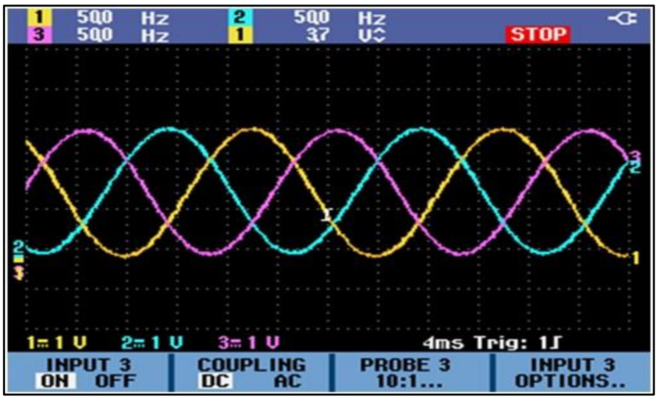

Fig 9 3 Phase Sinusoidal Signals with 120-Degree Phase Shift

➢ *Variable 3 Phase Inverter Signal*

Ability to adjust the frequency of a 3-phase signal is crucial for achieving variable speed control over the motor controlled by the Inverter. The system is also capable of generating a signal with adjustable frequency, controlled via push buttons on board which are multiplexed through the GPIO port. These buttons are programmed to incrementally adjust the frequency of the 3-phase signal with the help of Halogen using Pin multiplexing.

Debounce logic is added for any false triggering or multiple races around conditions that may cause the button to sense multiple noise inputs. By introducing a time delay of few milliseconds, we can ensure reliable adjustment preventing unintended frequency changes. These signals regulate the speed of motors by adjusting the frequency of the AC output waveform. By varying the frequency of the three-phase signal generated by the Inverter, the rotational speed of the motor is controlled.

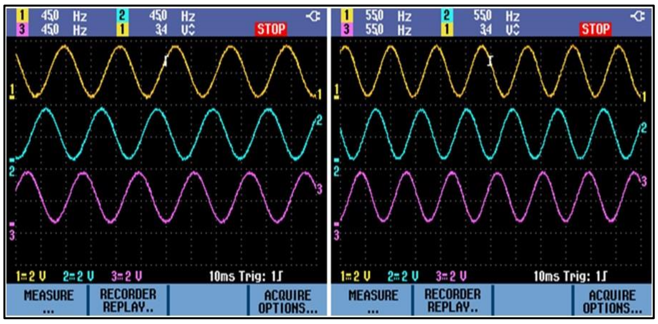

Fig 10 Variable Frequency 3 Phase Sinusoidal Signal

Higher frequencies increase motor speed, while lower frequencies decrease it. This precise control over frequency, facilitated by IGBTs switching enables efficient motor speed regulation across a wide range of uses in industrial automation and robotics. It also has the feature for gradual change in frequency rather than sudden changes causing problems to the Inverter or motor windings. A single push of this button will be responsible for changing the frequency of the sinusoidal waveform by 1 Hz per second. While keeping the phase angle and amplitude of all signals the same.

IV. eQEP MODULE

The eQEP (Enhanced Quadrature Encoder Pulse) module is a specialized hardware feature available on microcontrollers, designed for precise measurement of rotational speed using encoders. This module interfaces directly with quadrature encoders, which are commonly used in rotary applications such as optical encoders in the motors to provide position and speed feedback. It decodes the signals from these encoders to accurately determine the RPM, direction and position. The optical disk which is been used to generate the pulses.

➢ *eQEP Counter Input Modes*

Four modes can be used for the operation as per the requirement. Such as quadrature mode, direction mode, up count mode and down count mode. The quadrature decoder generates the direction and clock to the position counter in quadrature count mode. The encoders provide two square wave signals namely A and B which are 90 out of phase whose phase relationship is used to determine the direction of rotation of the input shaft and the number of pulses from the index to determine the speed. For forward or clockwise rotation, the Quadrature encoder pulse A (QEPA) signal leads Quadrature encoder pulse B (QEPB) signal and vice versa. In direction-count mode, direction and clock signals are provided directly from the external source. Some position encoders have this type of output instead of quadrature output.

The QEPA pin provides the clock input and the QEPB pin provides the direction input. In the Up-count mode, the counter direction signal is hard-wired for up-count and the position counter is used to measure the frequency of the QEPA input in the form of pulses which can be observed in Figure 11.

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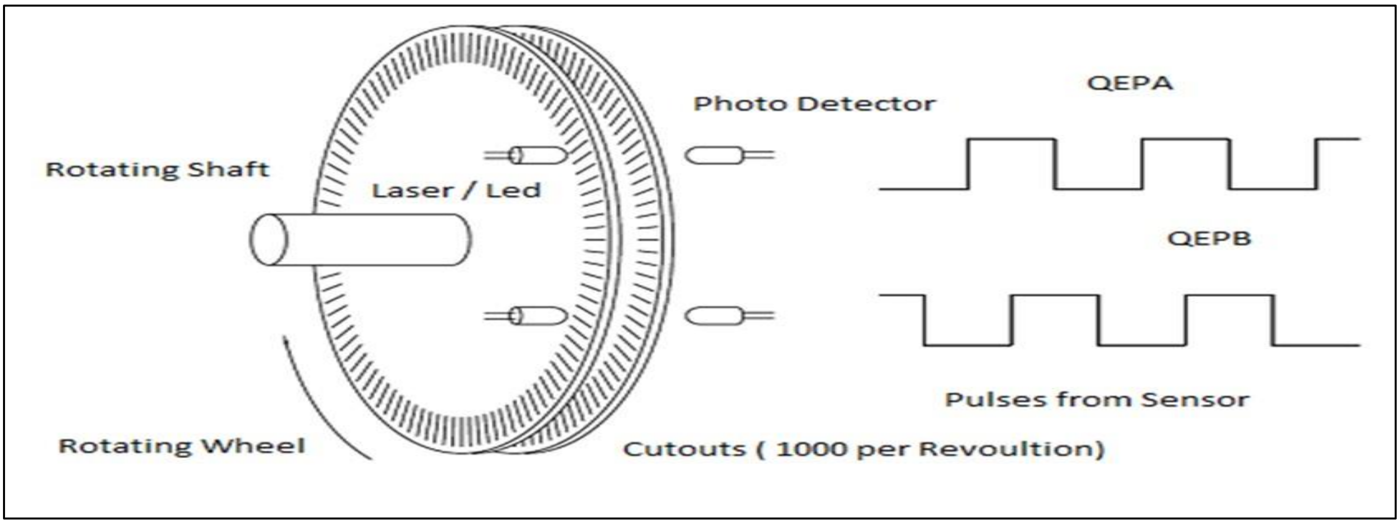

Fig.11 Optical Encoder Disk

This can be used for the precise measurement of the frequency resulting in the RPM of the motor. Also has an add-on feature that enables clock generation to the position counter on both edges of the QEPA input, thereby increasing the measurement resolution by 2x factor. The up-count mode as is most suitable for our application as a single signal is available for the detection which is not suitable for quadrature mode. Here the pulses are given to the count input QEPA and the TBPRD is calculated according to the input given. Using TBPRD we can calculate the frequency of the pulses and RPM of the motor given in the equation below.

$$Encoder\ freq = \frac{1}{(\mathrm{TBPRD}+1)\times TBCLK} \quad (12)$$

$$RPM = \frac{\text{Encoder freq}}{Encoder\ counts} \times 60 \quad (13)$$

V. RPM MEASUREMENT USING OPTICAL ENCODER

Detecting Revolutions Per Minute (RPM) using an optical encoder with the eQEP module on the Hercules can find application in various industries, particularly in Robotics, motor control, and Automation. Optical encoders provide high resolution and reliability in measuring angular displacement. In motor control systems, knowing the RPM of a motor shaft is crucial for closed-loop control which provides the RPM reading that is been controlled by the same system.

The eQEP module provides real-time feedback on the position and speed of the motor shaft, allowing the controller to adjust the motor's speed or position as needed. In robotics, where precise motion control is essential, RPM measurement using an optical encoder helps in tasks such as robotic arm movements, conveyor belt speed control etc.

An optical encoder typically consists of a rotating disk with slots or patterns that interrupt a light beam which can be a Laser or a LED pointing at a photo detector such as a photo diode or photo transistor. As the disk rotates, the interruptions generate pulses that are counted by the eQEP module. The eQEP module in the up-count mode does not provides the value of frequency of encoder pulses directly rather it gives a time base period value.

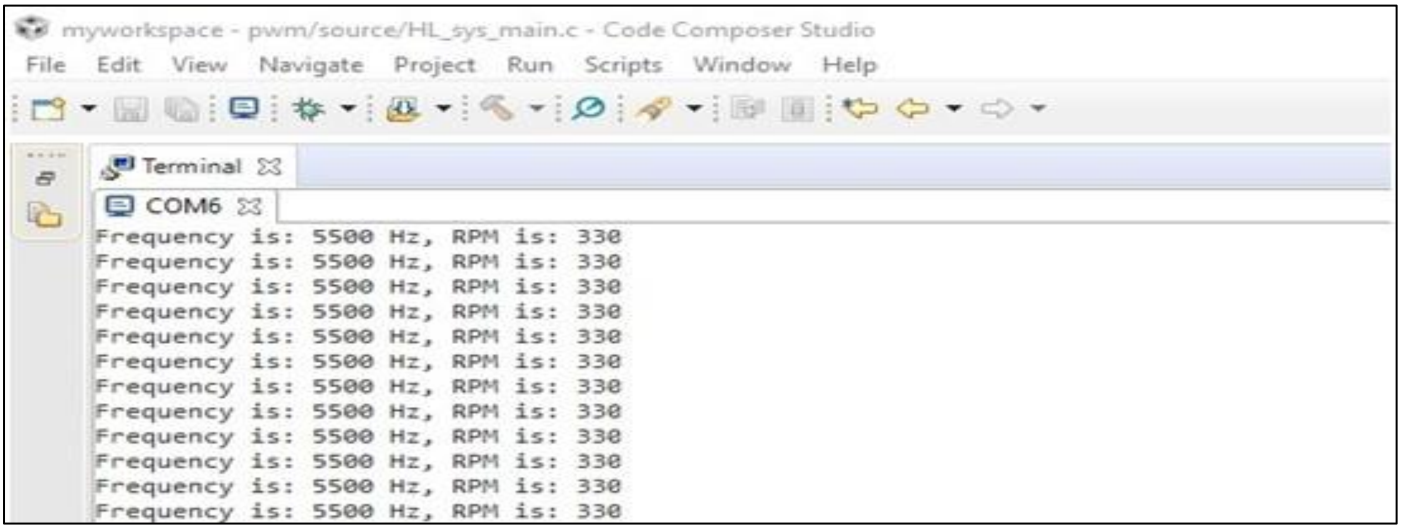

Fig 12 RPM Measurement and Printing on Console

The time base period value in our application was 13635.5 for 5.5 KHz of frequency. Then the Rpm is calculated based on the frequency which is 5.5 KHz having 1000 Encoder counts or cutout using the equation below,

$$Encoder\ freq = \frac{1}{(13635.5+1)\times 13.33\ Ns} \tag{14}$$

$$Encoder\ freq = 5.5\ KHz$$

$$RPM = \frac{5.5\ \mathrm{KHz}}{1000} \times 60 \tag{15}$$

$$RPM = 330\ Revolutions\ per\ minute$$

Where the Number of counts is the Encoder frequency and Encoder counts are the number of cutouts on the disk. The same value of RPM can be observed below in the Serial Monitor of the CCS. Which has been configured to provide the RPM reading at 5- second of intervals.

VI. CONCLUSION

This project successfully implemented PWM signal generation for a three-phase Inverter and precise RPM measurement using the Launchpad platform with HALCoGen and CCS. The ePWM module facilitated the generation of variable-frequency 3 phase signals, leveraging sub-modules like Time Base, Counter Compare, Dead Band delay, and Trip Zone for precise waveform control.

This functionality was effectively demonstrated on an oscilloscope, showcasing real-time frequency variation through user controls. Furthermore, the eQEP module enabled accurate RPM measurement using an optical encoder, translating shaft rotations into RPM readings with high precision. Signal processing techniques and careful calibration ensured reliable RPM calculations, validated against frequency measurements displayed in the CCS console.

In conclusion, this project seamlessly integrated hardware and software components to achieve robust functionality in both PWM signal generation and RPM measurement. Challenges in calibration and signal processing were systematically addressed, resulting in a successful demonstration of advanced Inverter control capabilities on the Launchpad platform.

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