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Varying Vector Pulse Width Modulation for Three Phase Inverter

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Abstract
This paper mainly deals with designing a control scheme to eliminate the OFF STATE (T0 state) present in a Space Vector Pulse-Width Modulation; this has been achieved by redesigning the equations for calculating the reference vector of modulating signal (Vref). In widely used Space Vector Pulse Width Modulation Vmax of carrier signal is greater than Vref of modulating signal (except when Vref = Vmax). Thus during this state the drive goes into the OFF STATE (T0 state). T0 States are similar mirror image states; hence they have no good or bad effect on the system. But there is an amount of switching loss occurring when the switch executes the T0 state. The new equations for reference vector resulted in reducing the switching losses to half the actual value. Also it has various other advantages like. Increase in DC-Link utilization from 15.47 to 21.14 at 2 KHz carrier frequency and Reduction in THD of the system compared to widely used SVPWM.

***Keywords**: SVPWM, NMSVPWM, Three Phase Inverter, Microcontroller*

1. Introduction

Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. Space Vector PWM (SVPWM) method is an advanced; computation intensive PWM method and possibly the best techniques for variable frequency drive application. The space vector PWM (SVPWM) is an alternative method used to control three-phase inverters, where the PWM duty cycles are computed rather than derived through hardware comparison like sine-triangle PWM reviewed in detail in further report. In SVPWM, the three-phase stationary reference frame voltages for each inverter switching state are mapped to the complex two-phase orthogonal α-β plane. The reference voltage is represented as a vector in this plane and duty-cycles are computed for the selected switching state vectors in proximity to the reference. In multilevel inverters, the number of switching state vectors increases and this additional complexity has prompted many attempts at optimizing the performance of the SVPWM method for multilevel inverters. This chapter focuses specifically on one simple multilevel SVPWM scheme which is relatively easy to implement in hardware. The aim is do a direct comparison with the other forms of control when applied to the New Modified Space Vector Pulse Width Modulation.

1.1 Drawbacks in using SVPWM

As described many other authors the major problem in conventional space vector pulse width modulation (SVPWM) is the high amount of switching losses, to compensate this some authors used methods like discontinuous SVPWM explained above. The switching losses are directly proportional to the number of switching in the T0 state which can be seen from the Figure 1. T0 state occurs when the amplitude of carrier signal is greater than the amplitude of the modulating signal.

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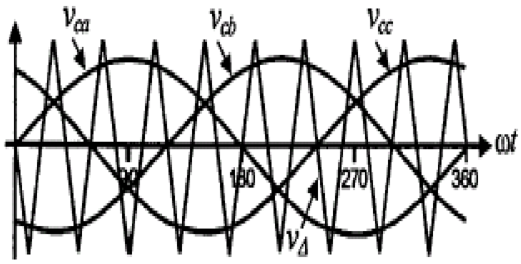

Figure 1. Three Phase modulating signal along with carrier signal

The operation time of the switching states depends on the amplitude of the carrier signal between particular phases, for example consider the brown line marked in the figure as an entire state Ts divided in four parts; T0/2, T1, T2, T0/2 respectively. Now the zone marked by the blue marker is state T1, the state marked by the green marker is state T2 and the states above green marker and below blue markers is T0/2.From the above problem description it is clear that if it could be possible to eliminate the T0 state, then we could reduce the switching losses. The work mainly deals with the elimination of this T0 states; it can be done by tracking the hexagonal sector instead of the circle touching the hexagon. The implementation of this method and the equations related to it has been explained in further work.

1.2 Classification of Various Methods

The reference vectors for various methods are shown in Figure 4.1, the reference vectors amplitude depends on the modulating index M which is the ratio of the modulating frequency to the carrier frequency. The reference vectors for various methods are shown in Figure 4.1, the reference vectors amplitude depends on the modulating index M which is the ratio of the modulating frequency to the carrier frequency

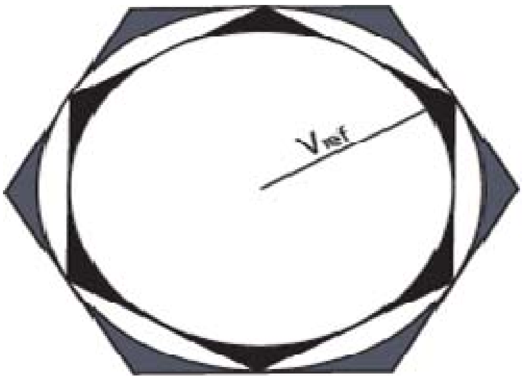

Figure 2. Various circle representations for different PWM techniques

The inner most circle represents the amplitude of reference vector of SVPWM with modulation index M=1. But if we track the outer sector instead of tracking any circle it would represent the proposed method, i.e. New Modified Space Vector Pulse Width Modulation (NMSVPWM) or it can be also called as Varying Vector Pulse Width Modulation (VVPWM) since in this case when we track the outer hexagon; the amplitude of the reference vector keeps on varying continuously, hence varying vector PWM.

1.3 Rotating Reference Vector

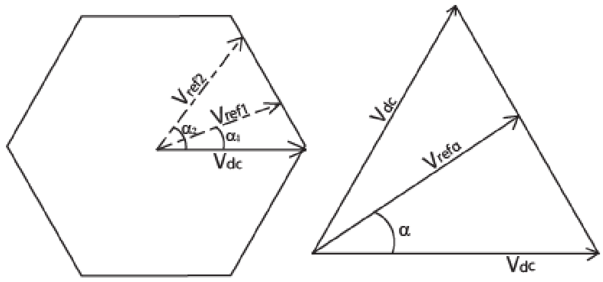

Figure 3. Reference voltage vector tracking for VVPWM

It can track the hexagon of the conventional SVPWM using below equations. The Figure 3 represents the amplitude of the rotation reference vector at various angles in sector-I. The amplitude of reference vector at a particular angle can be given by equations below. Since the structure is a hexagon, hence every sector is similar to other, also to calculate amplitude of reference vector in one sector is comparatively easy by using the triangle formulas as every sector is an isosceles triangle.

$$\alpha = \frac{\pi}{2} + tan^{-1}\left(\frac{Vq}{Vd}\right) \quad .... \quad (\text{ for } Vd \geq 0 \text{ }) \qquad (4.1)$$

$$\alpha = \frac{3\pi}{2} + tan^{-1}\left(\frac{Vq}{Vd}\right) \quad .... \quad (\text{ for } Vd \leq 0 \text{ }) \qquad (4.2)$$

$$\alpha_n = \alpha - \left[(n-1) * \frac{\pi}{3}\right]$$

For determining the value of the reference vector we need the DC link voltage along with the modulation index M and sector angle α. As the angle α increases from 0 to 30 degrees, amplitude of reference vector decreases whereas when the angle α increases from 30 to 60 degrees, the amplitude of reference vector increases. The average amplitude of the rotating references vector within a sector can be given by sum of average of the magnitude of all the reference vectors within that sector.

$$\mathbf{V_{ref} = m*\frac{3}{2}Vdc*}\left[\frac{sin\left(\frac{\pi}{3}\right)}{sin\left(\frac{2\pi}{3} - \alpha n\right)}\right]$$

The sector classification of the rotating vector based on the actual value of firing angle α is given by Table (1). The angle α determined after Clarks transform lies between 0 and 360 degrees, while for NMSVPWM this angle α should be divided into sectors of 60 degrees each. The reference vector is thus calculated by converting this angle α to a sector based angle αn for calculation

Table 1. Sector Identification Based On Angle A

Sector	Angle (α)
I	$0 \leq \alpha \leq \frac{\pi}{3}$
II	$\frac{\pi}{3} \leq \alpha \leq \frac{2\pi}{3}$
III	$\frac{\pi}{3} \leq \alpha \leq \pi$
IV	$\pi \leq \alpha \leq \frac{4\pi}{3}$
V	$\frac{4\pi}{3} \leq \alpha \leq \frac{5\pi}{3}$
VI	$\frac{5\pi}{3} \leq \alpha \leq 2\pi$

1.4 Switching States

There are six different switching states that occur in a 360 degree cycle, based on the ON times for T1 and T2 for various phases in various sectors. We here are considering a three phase system; hence there are three individual voltages Va, Vb and Vc as shown in below figure. The T0, T1, T2 states explained in below figures represent the on time for each voltage vector of Va, Vb or Vc corresponding to the three phases.

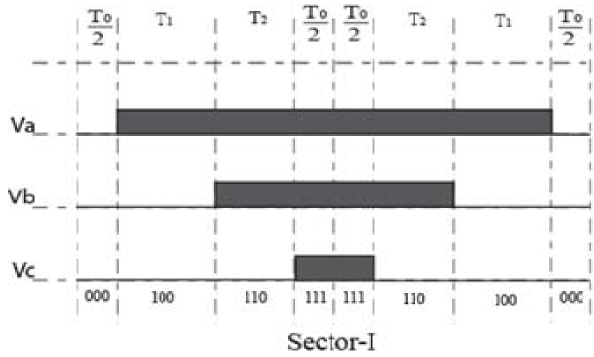

Figure 4. Switching states in sector-I of SVPWM

The entire switching state or the turn ON state is divided in eight different zones in conventional SVPWM as shown in Figure 4.4. If we observe the switching's in this sector, every phase switches two times in this sector. If the same is compared with the NMSVPWM we can observe that only phase Vb switches twice, while phase Va switches once and there is no switching in phase Vc. Thus we can clearly observe that the number of switching's per sector are reduced. If we observe an entire 360 degree cycle, i.e. all the six sectors, we will observe an reduction in switching states by 50% compared to SVPWM.

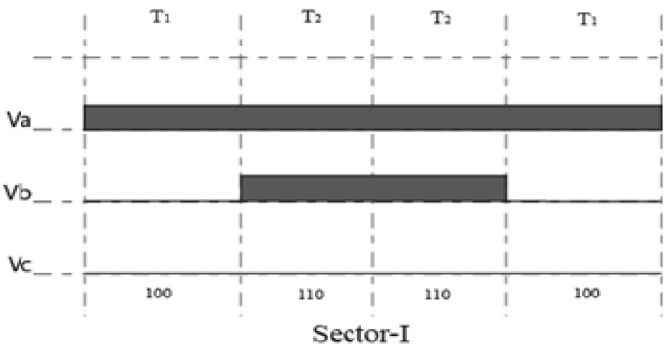

Figure 5. Switching states in sector-I of NMSVPWM

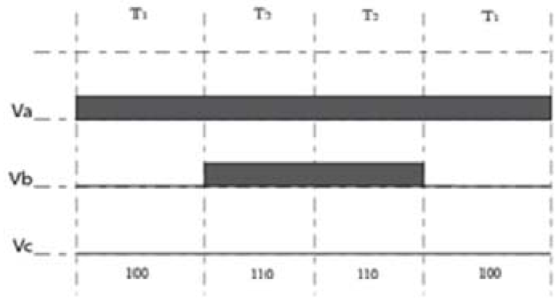

Figure 6. Switching of phases in sector-I of NMSVPWM

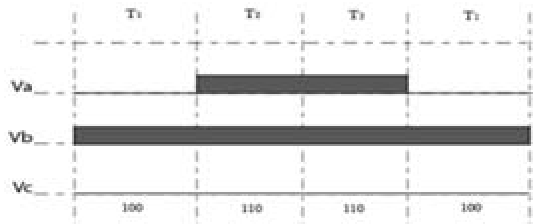

Figure 7. Switching of phases in Sector-II of NMSVPWM

Figure 8. Switching of phases in Sector-III of NMSVPWM

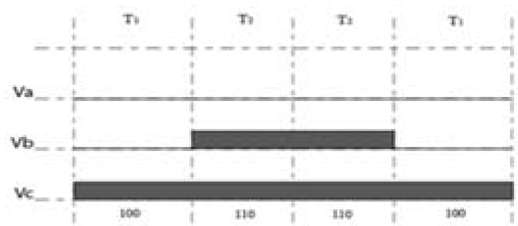

Figure 9. Switching of phases in Sector-IV of NMSVPWM

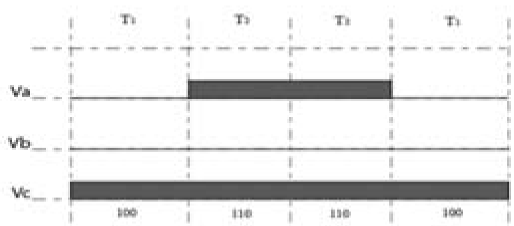

Figure 10. Switching of phases in Sector-V of NMSVPWM

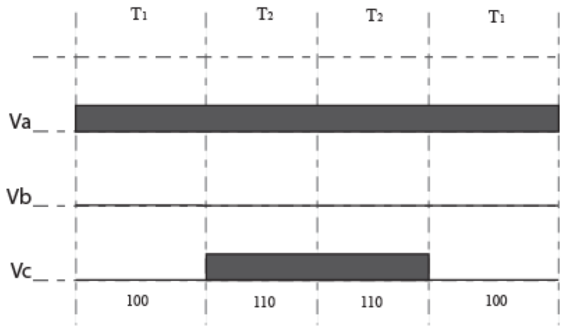

Figure 11. Switching of phases in Sector-VI of NMSVPWM

Figure 6 to Figure 11 represents the switching of phases Va, Vb and Vc based on T1 and T2 using the NMSVPWM technique. By observation of all the sectors we can say that if the T0 states are eliminated the switching's in individual phases can be reduced to half, i.e. each phase switches for 6 times within a cycle rather than 12 times in the conventional SVPWM.

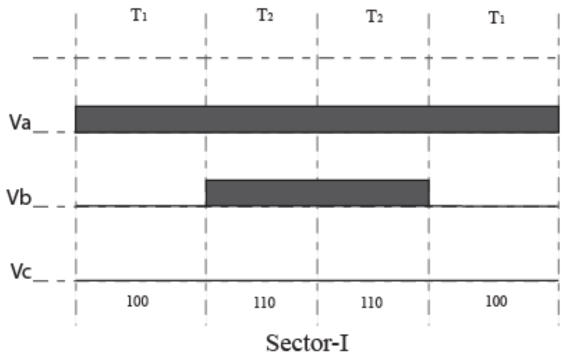

Figure 12. Switching of various phases for clockwise rotation of motor

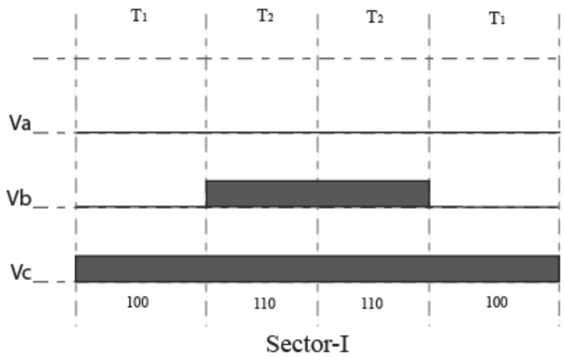

Figure 13. Switching of various phases for counter clockwise rotation of motor

The orientations shown in above figure represent the direction of rotation of motor loads. The changing of direction of motor using the NMSVPWM is very simple as seen from above two figures, Figure 12 represents the switching of phases for clockwise rotation of motor, while Figure 13 represents the switching of phases for counter clockwise rotation of motor.

2. Research Method

The scheme was implemented in MATLAB/SIMULINK; the model used for simulation is shown in Figure 4.14. The simulation was tried with various loads including the motor load and the results for them have been incorporated in chapter 5. The base circuit for both SVPWM and NMSVPWM is same the only difference in the two circuits is the equation to calculate the rotating reference vector values in the pulse time calculator block. Hence the major advantage of this scheme that we can reduce the switching losses of even previously implemented drives by slightly modifying their control algorithm, as a result the cost is not affected, also the other advantages found after the implementation of the scheme include boost in effective DC-Link utilization from 15.47% to 21.14% for 2 KHz operating frequency.

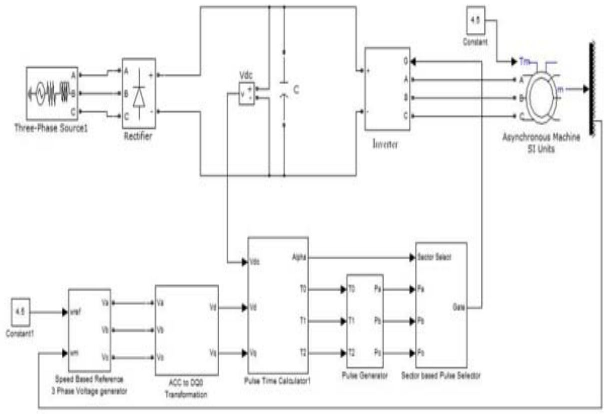

Figure 14. Simulation model used in MATLAB

3. Results and Discussion

The T0 state present in the conventional SVPWM technique can be observed in Figure 15. The topmost waveform is of the T0 state present in the system, which is followed by the middle T1 state waveform, and the bottom most waveform is of the T2 state.

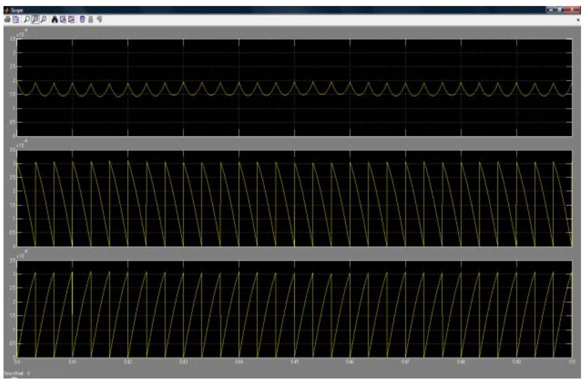

Figure 15 T0, T1, T2 state in conventional SVPWM

Comparing Figure 15 and Figure 16 we can observe that using the NMSVPWM method we can eliminate the T0 state just by changing the control algorithm and without making any hardware changes in the circuit. The time duration T0 eliminated from the circuit is compensated by the other two states T1 and T2 which can be observed from Figure.

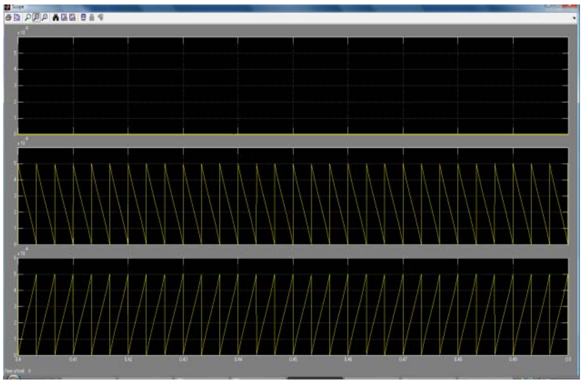

Figure 16. T0, T1, T2 state in NMSVPWM

The output voltages waveforms for three phase voltages Va, Vb, Vc are shown in Figure 17. The topmost waveform represents the phase A while the middle one represents the phase B and the bottom one represents phase C. The output current waveforms for simulation depends on the type of load used, here the waveform for an inductive load the representation for current waveforms is same as that for voltage waveforms, starting from top to bottom are phase A, phase B and phase C. The microcontroller output for the firing pulses for three phases is shown in Figure 19.

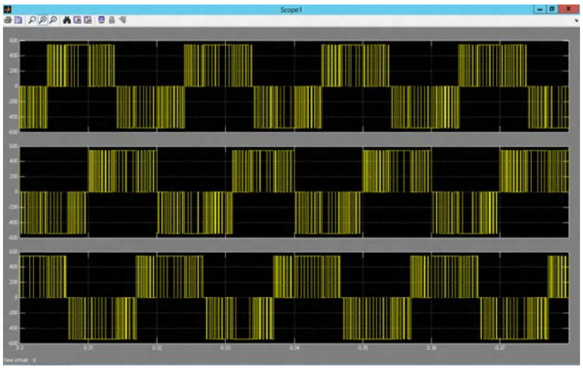

Figure 17. Voltage waveform of three phase output for RL Load

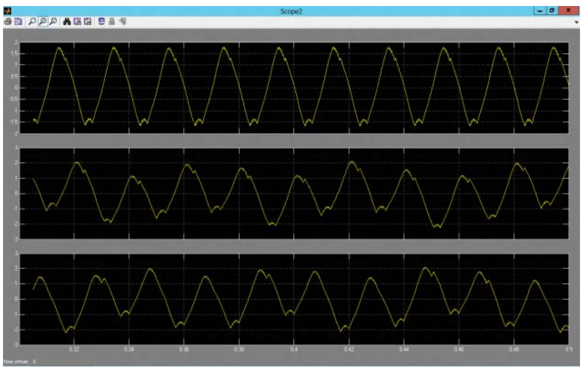

Figure 18. Current waveform of three phase output for RL Load

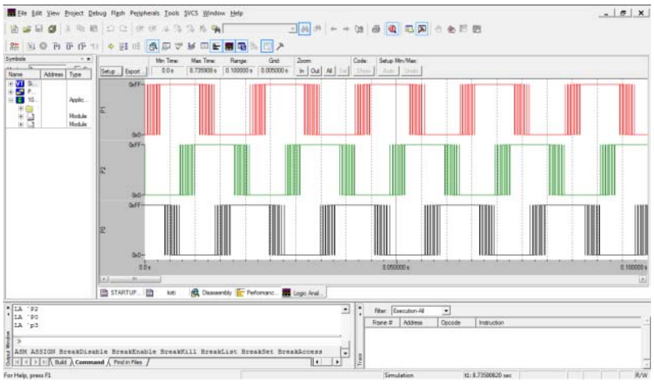

Figure 19. Microcontroller output using Keil

From the THD analysis of both NMSVPWM and SVPWM it is observed that using the new scheme reduces the Total Harmonic Distortion (THD) in the system. The input voltage THD for the commonly used SVPWM is 31.42% without filter, while for the NMSVPWM it is 31.30% without filter; which is 0.12% less than the SVPWM scheme. The other values for THD are shown in Table 2 comparing THD values for both the schemes with and without output filter for input side as well as for output side of the drive.

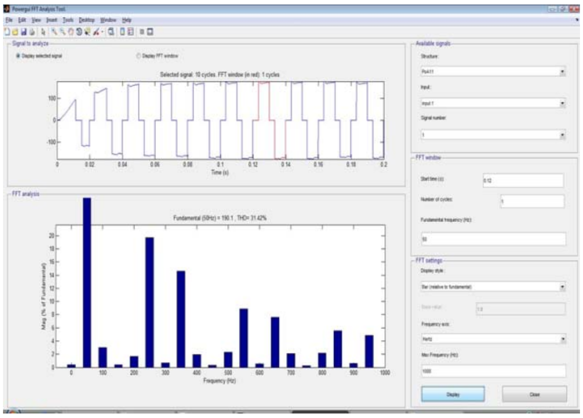

Figure 20. Microcontroller output using Keil

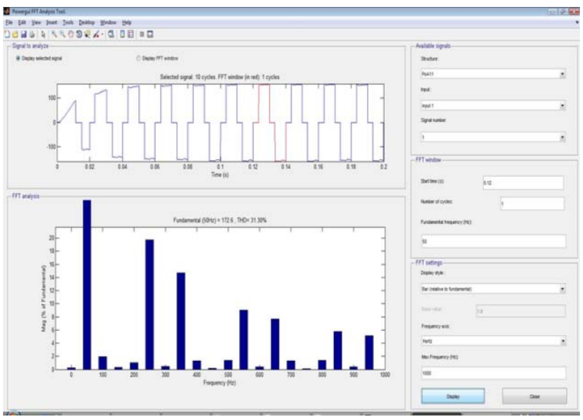

Figure 21. Microcontroller output using Keil

Table 2. THD Comparison of Both Systems

Sr.	Location	SVPWM	NMSVPWM
1	Input Voltage with filter	31.42%	31.30%
2	Input Current with filter	5.11%	4.34%
3	Output Voltage without filter	90.47%	73.95%
4	Output Current without filter	71.65%	64.7%
5	Output Voltage wi filter	34.46%	26.08%
6	Output Current wi filter	28.62%	20.96%

4. Conclusion

The work was carried out in three stages to complete successfully to achieve the above results. The equations were designed to compensate the switching losses by eliminating T0 states and tracking the hexagon. The equations were then tested on MATLAB/SIMULINK for verification and comparison with SVPWM method. Then a PATENT was filed and the design was sent to company's head R&D centre Germany for hardware testing and implementation.

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