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SVPWM Based VFD drive using 8- bit Microcontroller

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Abstract — Induction motors are the most widely used motors for appliances, industrial control, and automation; hence, they are often called the workhorse of the motion industry. They are robust, reliable, and durable. When power is supplied to an induction motor at the recommended specifications, it runs at its rated speed. However, many applications need variable speed operations. For example, a washing machine may use different speeds for each wash cycle. Historically, mechanical gear systems were used to obtain variable speed. Recently, electronic power and control systems have matured to allow these components to be used for motor control in place of mechanical gears.

Here an attempt is made to control the speed of Induction motor using generation of variable voltage variable frequency AC source (VVVF) using microcontroller & electronic devices.

These electronics not only control the motor's speed, but can improve the motor's dynamic and steady state characteristics. In addition, electronics can reduce the system's average power consumption of the motor.

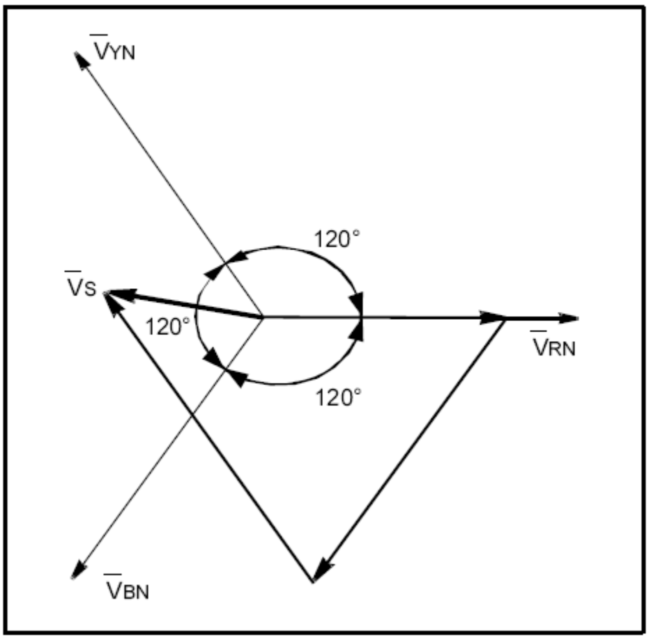
I. INTRODUCTION

VF control using the Sine PWM algorithm is a popular algorithm for AC induction motor control; however, this algorithm has certain drawbacks which affect the overall system efficiency. A more advanced switching algorithm, like Space Vector Modulation (SVM), over-comes the drawbacks of the Sine PWM algorithm and increases the overall system efficiency.

II. SPACE VECTOR MODULATION

The SVM is a sophisticated, averaging algorithm which gives 15% more voltage output compared to the Sine PWM algorithm, thereby increasing the VDC utilization. It also minimizes the THD as well as witching loss. Like Sine PWM, the SVM is also a scalar control. The direct controlled variables are the motor voltage and the motor frequency. The 3-phase line-to-neutral sine waves required for driving the 3-phase AC induction motor can be represented as 120° phase-shifted vectors (VRN, VYN, and VBN) in space, as shown in Figure 1.

FIGURE 1: 3-PHASE VOLTAGE VECTORS AND THE RESULTANT SPACEREFERENCE VECTOR



For a balanced 3-phase system, these vectors sum to zero. Therefore, they can be expressed as a single space reference vector (VS). By controlling the amplitude and the frequency of VS, the motor voltage and the motor frequency can be controlled. Hence, this algorithm is known as the SVM.

A typical block diagram of a VSI controlled by the C8051F120, which implements SVM, is shown in Figure 2. Point 0 is the midpoint of VDC (sometimes called the Virtual Neutral Point). For safe operation of the VSI, whenever one switch of a half bridge (Q1) is on, the other switch of the same half bridge (Q0) should be off and vice versa. This gives rise to eight distinct switching states of the VSI. Table 1 lists all the possible VSI switching states and respective line-to-neutral voltages.

FIGURE 2: BLOCK DIAGRAM OF C8051F120 MCU-CONTROLLED VSI

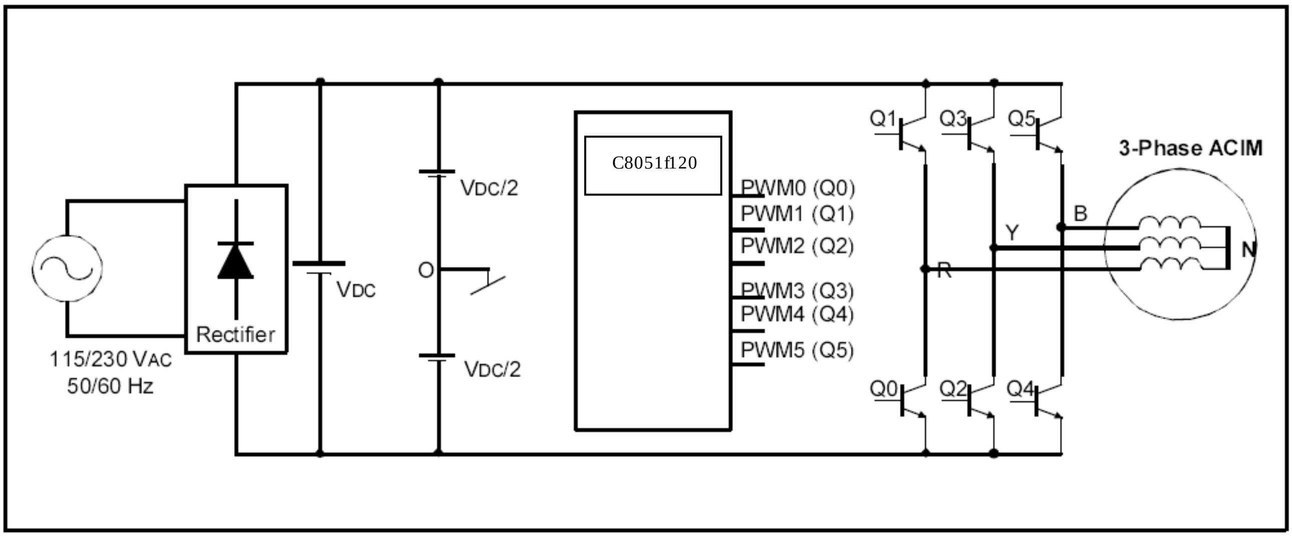
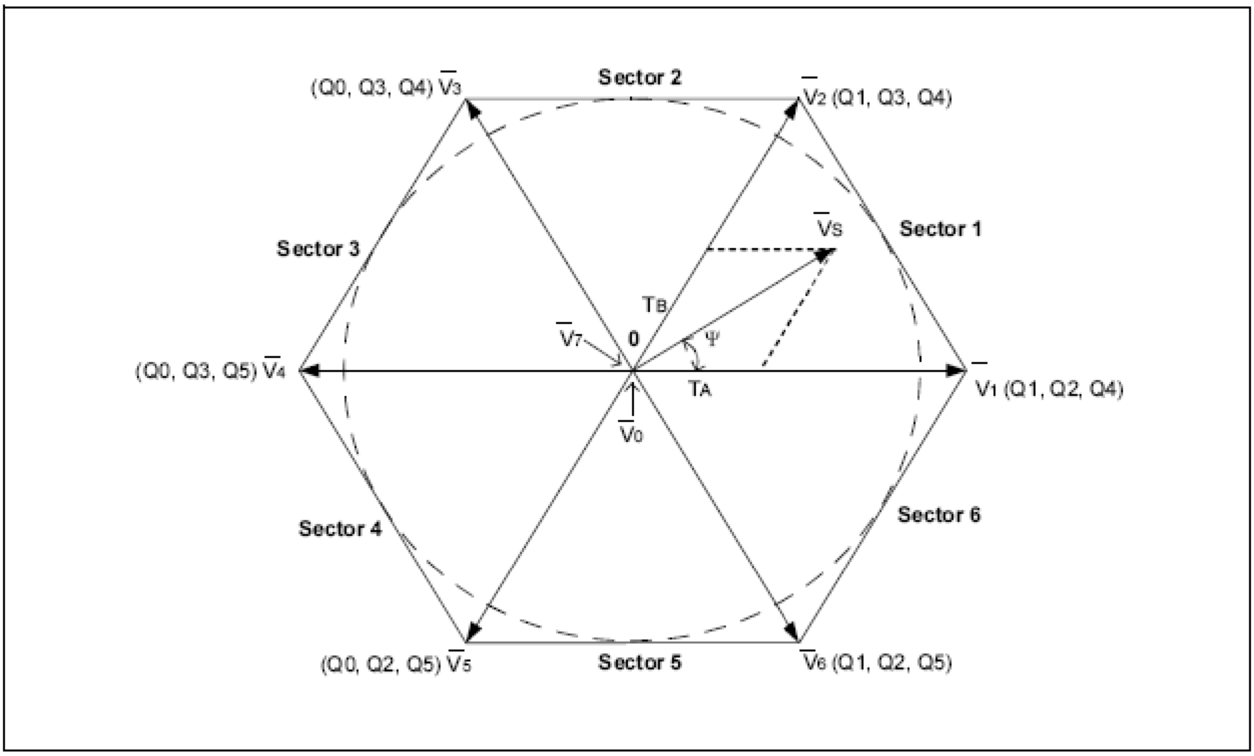


TABLE 1: VSI SWITCHING STATES AND RESPECTIVE LINE TO NEUTRAL VOLTAGES

Switching State	On Switches	V_{RN}	V_{YN}	V_{BN}	Space Voltage Vector
0	Q0, Q2, Q4	0	0	0	$\overline{V}_0$
1	Q1, Q2, Q4	2/3 V_{DC}	-1/3 V_{DC}	-1/3 V_{DC}	$\overline{V}_1$
2	Q1, Q3, Q4	1/3 V_{DC}	1/3 V_{DC}	-2/3 V_{DC}	$\overline{V}_2$
3	Q0, Q3, Q4	-1/3 V_{DC}	2/3 V_{DC}	-1/3 V_{DC}	$\overline{V}_3$
4	Q0, Q3, Q5	-2/3 V_{DC}	1/3 V_{DC}	1/3 V_{DC}	$\overline{V}_4$
5	Q0, Q2, Q5	-1/3 V_{DC}	-1/3 V_{DC}	2/3 V_{DC}	$\overline{V}_5$
6	Q1, Q2, Q5	1/3 V_{DC}	-2/3 V_{DC}	1/3 V_{DC}	$\overline{V}_6$
7	Q1, Q3, Q5	0	0	0	$\overline{V}_7$

As seen in Figure 3, the entire space is distinctively divided into six equal sized sectors of 60°. Each sector is bounded by two active vectors. V0 and V7 are the voltage vectors with zero amplitude and are located at the hexagon origin. VS is the resultant output due to the switching states of the VSI. For digital implementation of SVM, the VSI is switched at a very high frequency (FPWM). This frequency is high enough (>20 kHz) so as not to generate audible noise due to switching. FPWM decides the sample time TS for VS, where TS = 1/FPWM. There are various switching ways to generate VS from V0, V1...V7. When the VSI follows the switching state pattern, 1-2-3-4-5-6-1-2..., it is called the Six-Step PWM algorithm. This algorithm is easier to implement compared to all the other control algorithms. It can generate the line-to-line fundamental voltage more than the VDC. But this algorithm generates maximum THD. Also, the line-to-line and the line-to-neutral waveforms are not sine waves.

FIGURE 3: SPACE VECTOR HEXAGON



Different SVM Algorithms

There are various ways to implement the SVM, such as:

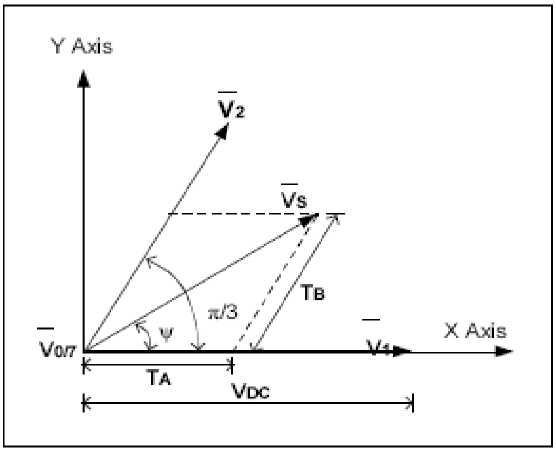
- Conventional SVM
- Basic Bus Clamping SVM
- Boundary Sampling SVM
- Asymmetric Zero-Changing SVM, etc.

All SVM algorithms have the same on time for active as well as inactive vectors. They differ mainly in the implementation of the inactive vectors, such as T0 and/or T7 distribution within TS.

Time Calculation to Generate VS

Let us take an example where VS is in Sector 1 at a vector angle (Ψ), as shown in Figure 4. It is assumed that during time TS, VS remains steady. For implementing the conventional SVM using SVM switching rules, VS is split as shown in Equation 1. Equation 1 means that the VSI is in active state 1 for TA time and it is in active state 2 for TB time. For the remaining time of TS, no voltage is applied. This can be achieved by applying inactive state 0 (or 7) for the remaining time T0 (or T7).

FIGURE 4: VECTOR Vs IN SECTOR 1



Equation – 1

$$\boldsymbol{Vs} = \left[\frac{\boldsymbol{Ta}}{\boldsymbol{Ts}} \times \boldsymbol{V1}\right] + \left[\frac{\boldsymbol{Tb}}{\boldsymbol{Ts}} \times \boldsymbol{V2}\right] + \left[\frac{\boldsymbol{T0/7}}{\boldsymbol{Ts}} \times \boldsymbol{V0/7}\right]$$

The time intervals, TA, TB and T0/7, have to be calculated such that the average volt seconds produced y the vectors, V1, V2 and V0/7 along the X and Y axes, are the same as those produced by the desired reference space vector VS.

The modulation index or amplitude ratio is defined as:

M= Vs/Vdc

where |VS| is the amplitude or the length of VS. Resolving VS along the X and Y axes, we get:

Equation – 2

$$(Vdc * Ta) + \left(Vdc * \frac{cos\pi}{3} * Tb\right) = Vs * cos\psi * Ts$$

$$Vdc * \frac{sin\pi}{3} * Tb = Vs * sin\psi * Ts$$

Solving for Ta & Tb We get:

Equation – 3

$$\frac{Ta}{Ts} = \frac{2}{\sqrt{3}} * M * \sin\left(\frac{\pi}{3} - \psi\right)$$

$$\frac{Tb}{Ts} = \frac{2}{\sqrt{3}} * M * \sin\psi$$

$$Ts = Ta + Tb + T0/7$$

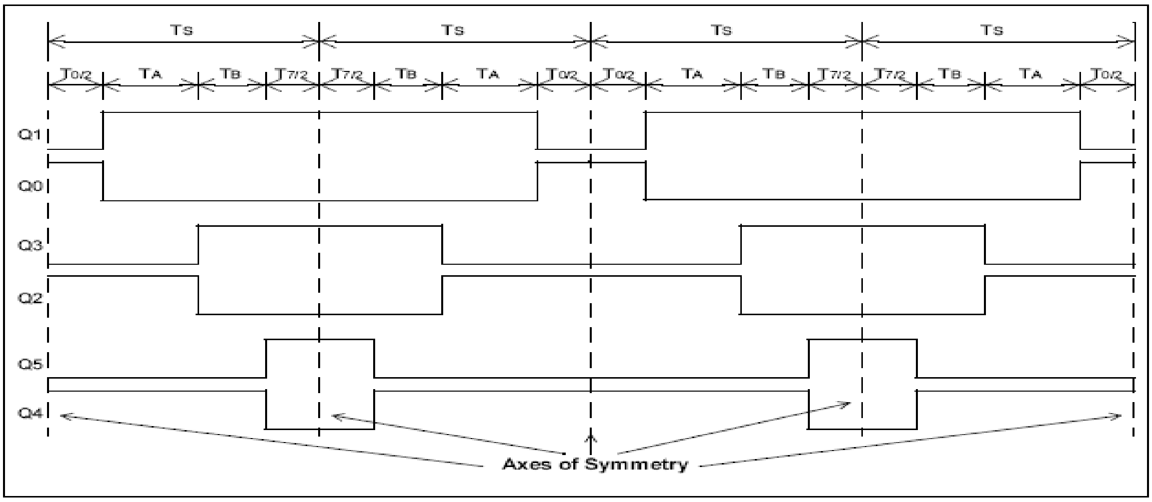
T0/7 can be found from Equation 3. For better THD, T0(or T7) is split into two and then applied at the beginning and at the end of the TS. The typical VSI switching wave forms in Sector 1, as defined by Equation 3 and the switching rules for the conventional SVM using center aligned PWM, are as given in Figure 5.

We can observe the different axes of symmetry in all the waveforms as shown in Figure 5. These symmetries are mainly responsible for having lower THD in SVM compared to Sine PWM in the linear operating region.

From Figure 3, it is clear that in the linear operating region, the maximum line-to-line voltage amplitude can be achieved when VS is rotated along the largest inscribed circle in the space vector hexagon. In mathematical terms, this is equivalent to:

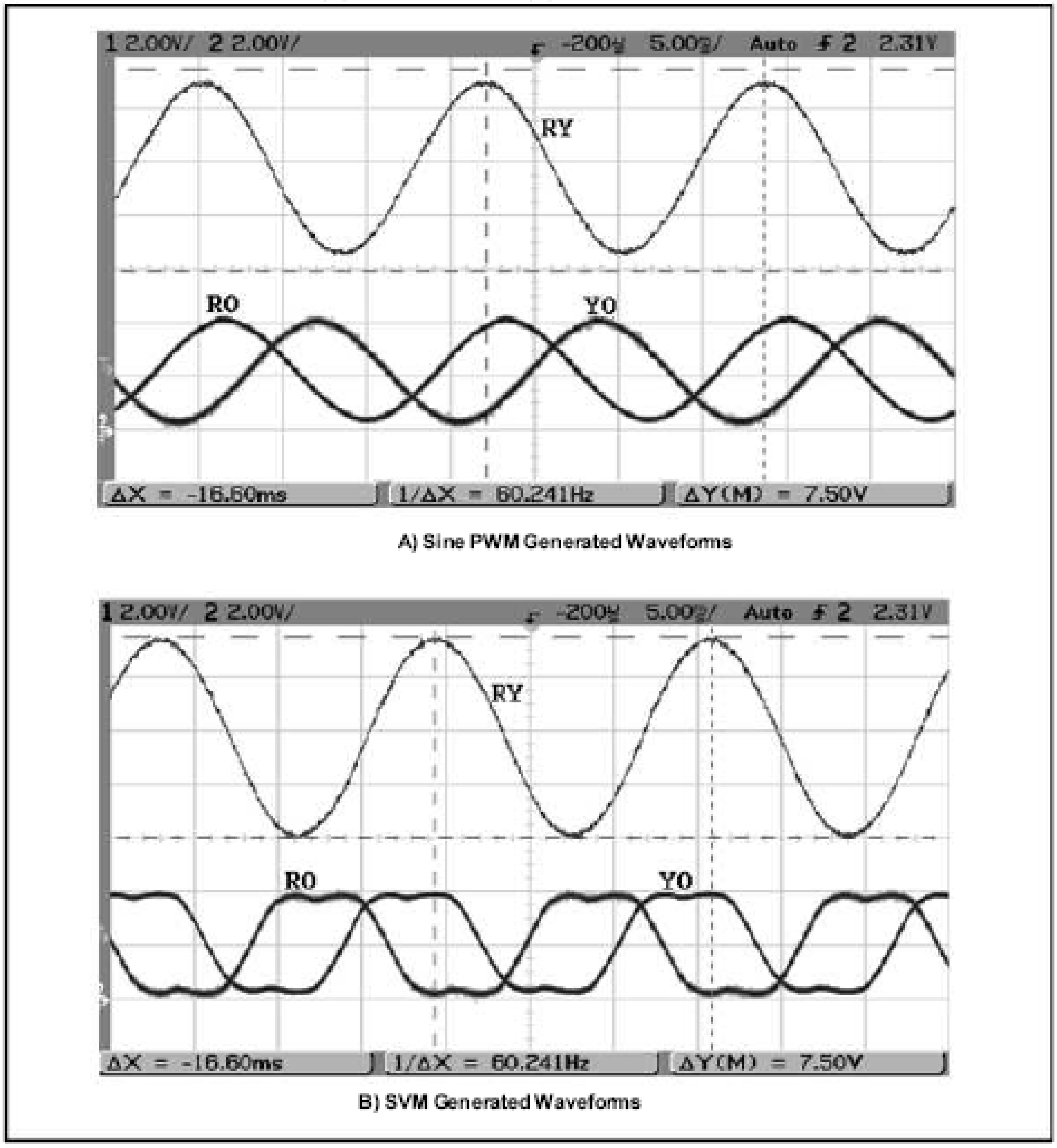
$$Mmax = Radius\ of\ largest\ Inscribed\ circle/Vdc$$

FIGURE 5: TYPICAL VSI SWITCHING WAVEFORMS IN SECTOR 1



The reason for the higher line-to-line voltage in SVM can be explained with the help of Figure 6. It shows the phase voltage (line-to-virtual neutral point) generated by Sine PWM and SVM. For clarity, only two phase voltages (RO and YO) and their resultant line-to-line voltage (RY) are shown in each figure. The Sine PWM generated phase voltages are sine waves. With 120° phase shift between them, the resultant line-to-line voltage is approximately 86.6% of VDC. But, the SVM generated phase voltages have a third harmonic component superimposed on the fundamental component. The addition of this harmonic component is due to the effective usage of inactive states which is not possible in the Sine PWM. With 120° phase shift between them, the third harmonic component is cancelled out in the resultant line-to-line voltage in such a way that the resultant line-to-line voltage is boosted to VDC (100%). Thus, SVM generates line-to-line voltage with higher amplitude (about 15% more) compared to Sine PWM.

FIGURE 6: GENERATED PHASE VOLTAGES AND CORRESPONDING LINE-TO-LINE VOLTAGE IN (A) SINE PWM AND (B) SVM



A) Sine PWM Generated Waveforms

B) SVM Generated Waveforms

Advantages of SVM

The advantages of SVM vis-a-vis Sine PWM are as follows:

- Line-to-line voltage amplitude can be as high as VDC. Thus, 100% VDC utilization is possible in the linear operating region.
- In the linear operating range, modulation index range is 0.0 to 1.0 in the Sine PWM; whereas in the SVM, it is 0 to 0.866. Line-to-line voltage amplitude is 15% more in the SVM with the modulation index = 0.866, compared to the Sine PWM with the modulation index = 1. Hence, it has the better usage of the modulation index depth.
- With the increased output voltage, the user can design the motor control system with reduced current rating, keeping the horsepower rating the same. The reduced current helps to reduce inherent conduction loss of the VSI.
- Only one reference space vector is controlled to generate 3-phase sine waves.
- Implementation of the switching rules gives less THD and less switching loss.
- Flexibility to select inactive states and their distribution in switching time periods gives two degrees of freedom.
- As the reference space vector is a two-dimensional quantity, it is feasible to implement more advanced vector control using SVM.

III. HARDWARE USED FOR SVM AND DIGITAL IMPLEMENTATION

A SILAB C8051F120 Development Board is used to develop and test the SVM control. The C8051F120 MC is a 100MIPS controller with 6 PCA modules. A 3-phase IGBT-based inverter bridge is used to control the output voltage from the DC bus. The control circuit and power circuits are optically isolated with respect to each other. An on-board flyback power supply generates +5 VD, with respect to the digital ground used for powering up the control circuit, including the MC device. The +5 VA and +15 VA are generated with respect to the power ground (negative of DC bus). With optical isolation between the power and the control circuits, the programming and debugging tools can be plugged into the development board when main power is connected to the board. The board communicates with a host PC over a JTAG port configured with an on-chip JTAG Debugger.

To implement the SVM in the digital domain, the power control PCA module of the C8051F120 is utilized. The module provides up to 6 PWM output channels with the dedicated PWM timer as its time base. The module has the capability to generate center aligned PWM with 16-bit resolution. This is the most important feature required for the SVM implementation. VS needs to be created and rotated in space for SVM implementation. To approximate the position of VS, Equation 3 and the previously mentioned switching rules are utilized. Looking at Equation 3, one will notice that in the same sector, TA and TB are inverted with respect to each other. Hence, only one look-up table with time entries is needed. A look-up table with TB entries is created. The size of the look-up table is decided by the angle resolution used. The total sector angle is 60°. To get a good resolution with an 8-bit microcontroller like the C8051F120, the entire sector is divided into 256 points, giving an angle resolution of 0.234°. The center aligned PWM is used for better THD (FPWM = 1/2 * TS).

The required motor speed in Hz is decided by the rate at which the VS is rotated. For this purpose, it is necessary to find both the vector angle and the vector update step size. To speed up the online calculations, the constant, DEGREE_CONSTANT, is defined; this is then used to calculate the vector update step size and the vector angle as shown in Equation 4.

Equation - 4

$$\text{DEGREE\_CONSTANT} = (360 \times 256 \times \text{Multiplication Factor})/(60 \times F_{PWM})$$

$$\text{Vector Update Step Size} = \text{DEGREE\_CONSTANT} \times \text{Required Motor Speed (Hz)}$$

$$\text{Vector Angle} = \text{Vector Angle} + \text{Vector Update Step Size}$$

Looking at the definition of DEGREE_CONSTANT, one will notice that its value, without any multiplication factor, will result in a fractional number less than unity for FPWM > 1.536 kHz. Almost all motor control applications have FPWM much higher than 1.536 kHz. Handling a fractional number with any 8-bit microcontroller will require more CPU processing time. This requirement is difficult to meet in the SVM implementation, where VS is updated at every TPWM (= 1/FPWM) time interval. At the same time, the multiplication factor value needs to be such that its post-calculation adjustment requires the least possible microcontroller processing time. It is proposed that the multiplication factor be 256. This will result in a 16-bit value for the vector update step size and hence, 16-bit vector angle pointer (VECTOR_ANGLE<MSB:LSB>). As an adjustment for the multiplication factor, VECTOR_ANGLE_LSB is discarded. VECTOR_ANGLE_MSB is used as the table pointer for reading the value of TA and TB from the lookup table. Whenever a carry is generated due to the Equation 4 addition, it physically means that the VS has advanced to the next sector and hence, the sector count (SECTOR_NO) is incremented by one. The motor voltage is decided by the amplitude of VS (modulation index m). To implement the same digitally, values of TA and TB are multiplied by m. Based on TS, TA and TB, the duty cycle values for all 3 phases (R, Y and B) are calculated as shown in Table 2. Equations shown in Table 2 for Sector 1 are evident in Figure 5. Similarly, equations for other sectors are derived with the switching rule constraints.

TABLE 2: DUTY CYCLE VALUES FOR THE THREE MOTOR PHASES BASED ON V_S LOCATION

Sector No.	Phase R Duty Cycle	Phase Y Duty Cycle	Phase B Duty Cycle
1	$T_0/2$	$T_0/2 + T_A$	$T_S - T_0/2$
2	$T_0/2 + T_B$	$T_0/2$	$T_S - T_0/2$
3	$T_S - T_0/2$	$T_0/2$	$T_0/2 + T_A$
4	$T_S - T_0/2$	$T_0/2 + T_B$	$T_0/2$
5	$T_0/2 + T_A$	$T_S - T_0/2$	$T_0/2$
6	$T_0/2$	$T_S - T_0/2$	$T_0/2 + T_B$

IV. CONCLUSION

VF control using the SVM in the open loop is more energy efficient compared to the Sine PWM. With an on-chip dedicated motor control peripheral like the PCA PWM module and the rich instruction set, the C8051F120 is well suited to give a low-cost solution, implementing the VF control using the SVM algorithm for the 3-phase AC induction motor control. In addition, the on-chip resources, such as the ADC and the multiple timers, allow users to implement other control (acceleration and deceleration) and protection (over current, overvoltage, over temperature) features.

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