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Design and Implementation of Low Cost Sensor-less PM Synchronous Motor Drive for Pump and Compressor Applications

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ABSTRACT

Design and implementation of a low cost control scheme of sensor less Permanent Magnet Synchronous Motor (PMSM) for efficiency improvement of pump and compressor is presented in this paper. The main problems of sensor less control of PMSM are starting jerk and loss of synchronism during acceleration. Due to absence of rotor position sensor, controller has to start the motor from an arbitrary initial rotor position and mismatch between actual position and assumed position is the principle reason behind starting problem. It is described in this work how a simple modification in motor turn-off process can solve the aforesaid problem. On other hand, loss of synchronism problem occurs mainly due to improper selection of rate of change of stator voltage and frequency. The previously described simple procedure is used to determine the optimal rate of change of stator voltage and frequency. Experimental results are presented to demonstrate effectiveness of the proposed control scheme.

Keywords*:* PMSM, Sensor-less Control, SPWM

INTRODUCTION

Permanent Magnet Synchronous Machine (PMSM) [1-2] has several advantages over induction motor such as superior efficiency, high power density, low rotor inertia, improved power factor, small size and weight and more robust construction [3-4, 6, 9]. The main motivation behind use of PMSM for applications like fan, blower, pump, air-condition and refrigeration system is its superior efficiency, small size and weight [6,8]. However, the obstacles are PMSM is not line start like induction motor, relatively complex control characteristics compared to induction motor. Control electronics and inverter is also necessary for operation of this type of motor [5-6]. Nowadays application of PMSM is increased due to reduction in cost of power electronics and digital electronics components and development of high grade permanent magnet materials [6, 9]. Self-control or vector-control PMSM drives are used where high dynamic performance is required like servo and robotic drives, electric vehicles, starter/generator for aircraft engines etc. [5-6, 9]. However, rotor position information is required for self or vector control of PMSM [5-6]. To acquire this position information, optical encoder or resolver is generally used [5]. In vector controlled PMSM drives, presence of rotor position sensor increases the cost and complexity and at simultaneously it reduces the reliability and robustness [6, 9-10].

A large number of research works are going on for rotor position sensor-less operation of the PMSM [10-38]. There are different sensor-less control techniques reported in literature such as back EMF based estimation [10-15], stator third harmonic voltage based estimation [6][9], Model Reference Adaptive Control [16-18], Full order state observer [19-20], Sliding-Mode Observer [21-22], Extended Kalman Filter [23] based estimation, Rotor saliency based technique [24-28], High frequency signal injection based technique [29-37] etc. However, implementation of these techniques requires costly resources like DSP, FPGA etc. Moreover, voltage and current feedbacks are also required for these types of control techniques which further increase the cost and complexity of the drive. As a result, it restricts low cost application like fan, blower, pump, air-condition, refrigeration system in spite of its better efficiency. Hence a simple low cost open loop control technique of PMSM without rotor position sensor and current, voltage or flux feedback is required for the efficiency improvement of above mentioned applications where precision speed, position or torque control is not necessary.

Design and development of a simple PMSM drive without any feedback signal is described in this work. Absence of any kind of feedback mechanism makes this drive truly sensor-less and also decreases the cost and complexity considerably. Principal problems of sensor-less open-loop control for PMSM are identified as starting jerk or temporary reverse movement at the time of starting [26] and loss of synchronism during acceleration [38]. Due to the absence of rotor position information, controller has to start the motor from an arbitrary rotor position. The direction of starting torque depends on error between actual initial rotor position and assumed position. If it is more than 90°, then starting torque will be in the opposite to the desired direction of rotation and causes starting jerk or temporary reverse movement which is harmful to the mechanical integration of the motor load system. It is described in this work how a simple modification in motor turnoff process can solve this problem. On the other hand, loss of synchronism problem occurs mainly due to improper selection of rate of change of stator voltage and frequency. A simple solution of this problem is described in [38] where a trial and error based experimental procedure is developed to determine the optimal value for rate of change of stator voltage and frequency. In [38], space vector PWM (SVM) technique is used to control the voltage source inverter (VSI) however in this work sinusoidal PWM (SPWM) is used to keep the control algorithm comparatively easy to implement. This modification will somewhat degrade VSI output waveforms however this affects drive performance negligibly for low performance application. A prototype has been developed to examine effectiveness of the proposed control scheme.

PROBLEM ANALYSIS AND CONTROL STRATEGY

The main objective of proposed sensor-less control strategy is to overcome synchronization problem and starting jerk or temporary reverse rotation problem. A PMSM is nothing but a synchronous motor with PM rotor. As a result, motor average starting torque is zero when supplied with a 3-phase ac supply of 50/60Hz. This problem can be solved by using Self-control technique or Field oriented control technique. However, these techniques require direct or indirect rotor position information for their operation, which increases cost and complexity of the drive. A simple open loop sensor less control method is discussed by the authors in [38] to solve the loss of synchronization problem. In this method, the motor is started by reducing stator frequency to a very low value and its frequency is gradually incremented to increase the speed. The motor acceleration is dependent on rate of change of stator frequency (Δf). The motor is operated with different values of Δf to achieve different acceleration rate. Starting from a very low value, Δf is increased every time. However, this rate is not changed during a particular acceleration process i.e. every time after starting from rest up to rated speed, Δf remains same. The motor is accelerated from standstill to rated speed with different values (increased) of Δf. It is observed from the experiment that there is a threshold value of Δf above which the magnetic locking between stator and rotor pole breaks and motor loses its synchronism. This threshold value of Δf is the most appropriate value of Δf, for a particular motor. Motor terminal voltage is also varied proportionally to frequency for keeping flux linkage constant. However, this method suffers from the starting problem i.e. initial starting jerk or temporary reverse motion. The reason of this problem is wrong orientation of stator magnetic field with respect to rotor field or rotor position (as in PM motor rotor field is fixed with the rotor) at the time of starting from stand still. Due to the absence of rotor position sensor, initial rotor position information is not available to controller at the time of starting and the controller has to start the motor with an arbitrary stator field orientation. The process of orientation of stator field using a digitally controlled 3 phase voltage source inverter (VSI) is discussed in Section-III. If the position error is less than 90°, the motor developed torque will be positive and smooth starting will be observed, otherwise a jerk or temporary reversed rotation may occur. The concept can be explained with the help of figures (fig.1 to 3).

In fig.1 the bold lines indicate the arbitrary stator magnetic pole positions (S1-N1-S2-N2) and the direction of torque is shown for different position of rotor ‘S’ pole (Sr). It can be observed from the fig.1 that developed torque is positive when the rotor ‘S’ pole situated in the second and forth quadrant i.e. the angle between the stator ‘N1’ pole and rotor ‘Sr’ is less than 90° or stator ‘N2’ pole and rotor ‘Sr’ is less than 90°. However, if the rotor pole ‘Sr’ situated in first or third quadrant then starting torque will be in opposite direction. It can be observed from fig. 2 and fig.3 that although the initial starting torque is in the opposite direction, as the stator field moves forward the torque direction change and motor will continue its rotation. Therefore, starting failure will not occur. However, depending on the angular difference between stator and rotor pole, starting jerk (fig.2) or temporary reverse rotation (fig.3) may occur. So, for the very first time when the motor will start, starting problem may occur depending on the relative initial position of the rotor with the stator pole position. To eliminate the possibility of starting jerk, from second time onward, a state-of-the-art turn-off process is adopted. Generally, to turn-off, motor power is directly switched off, hence motor can stop at any unknown rotor position and when the motor will be started again, no information of rotor position is available to the controller. As a result, the controller starts the motor with an arbitrary predetermined stator pole orientation. So the starting problem may again occur. It is clear from the above discussion that there is a possibility of starting jerk or temporary reverse rotation of the motor whenever the motor will be started. The application like fan, blower, pump, air-condition and refrigeration system requires frequent start and stop. So starting problem of sensor-less PMSM will have adverse effect on this type of applications. This problem can be solved by using a controlled turn-off process.

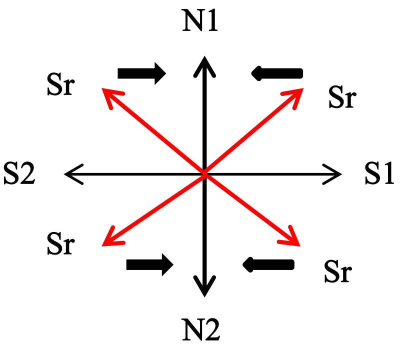

Fig. 1 Direction of different position of rotor field

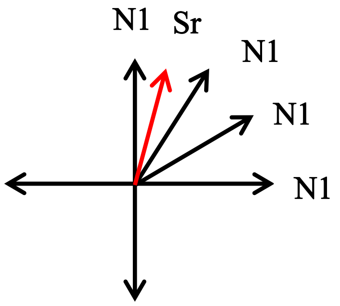

Fig. 2 Process starting of motor when the rotor 'S' in first quadrant with small angle between stator and rotor poles

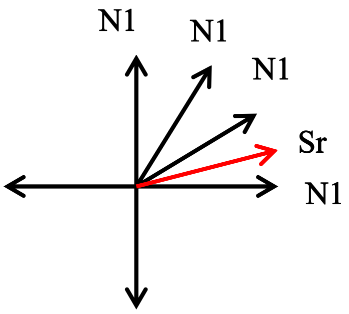

Fig. 3 Process starting of motor when the rotor 'S' in first quadrant with large angle between stator and rotor poles

In this process motor power is not switched of instantaneously, but when stop command is given, controller will gradually decrease stator frequency and voltage in the same fashion as in case of start-up operation. At the end of this turn-off process, frequency and voltage will become zero and therefore motor will stop. As the motor is stopped by the controller itself, the end position of stator pole and rotor pole is in locked condition i.e. the angle between the stator pole 'N_1' and rotor pole 'Sr' is zero. After this, motor power supply can be switched off. The rotor will tightly hold the same position due to attraction forces between the PM rotor and static part of the motor unlike induction or wound field synchronous motor. Now when the motor is started again there will be no starting jerk or reverse rotation as the angle between stator pole 'N_1' and rotor pole 'Sr' is zero. However, this type of control technique is only applicable for fan, blower, pump, air-condition and refrigeration system but not applicable for overhauling load like electric traction, electric vehicle etc.

CONTROL OF ROTATING MAGNETIC FIELD USING INVERTER

In this section, control technique of orientation, speed and direction of rotation of the stator magnetic field is explained. Schematic diagram of a 3-phase inverter consisting of six MOSFETs is shown in fig. 4. A four pole star connected isolated natural stator is considered here. However, this analysis can also be extended for any number of stator poles. Here A, B and C are three stator phases and A1-A1', A2-A2', B1-B1', B2-B2', C1-C1', C2-C2' are the six coils which are connected as shown in the fig.5 to create the 4 pole stator winding.

Now, considering an instance when switches M1, M5 and M3 are ON and the stator phase 'A' and 'C' are connected with the positive and 'B' is connected with the negative of DC supply. As a result, excitation current enters through terminals A1, A2 and C1, C2 and leaves through B1, B2. Terminals of same current direction can be grouped together to realize the flux direction. How four poles are generated can be observed from fig.6. Similarly, when switches M4, M5 and M3 are ON, excitation current enters through phase 'C', and leaving through phases 'A' and 'B'. The terminals are again grouped together as discussed before to create 4-poles as shown in fig. 7. However, after comparing fig.6 and fig.7, it can be observed that there is a 60° (elec.) rotation of poles in clockwise direction**.** The rotation of the stator poles can be completed if the stator phases are excited in a proper sequence as shown in fig.8 to fig.11. The switching states of all the MOSFET switches are given in Table-1 to realize all six sequences.

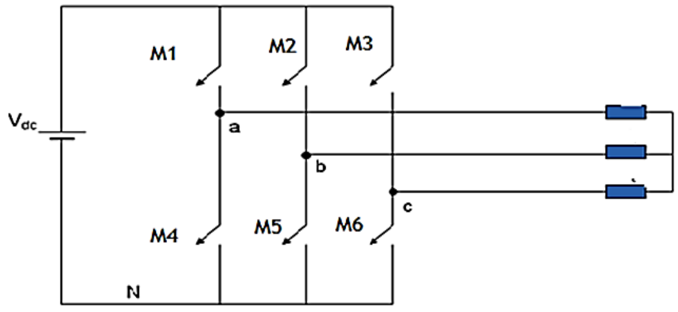

Fig. 4 Inverter Circuit

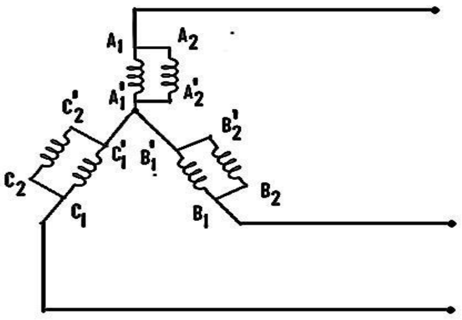

Fig. 5 Four pole Stator Winding

Complete mechanical rotation of the stator magnetic field can be achieved by repeating the sequence (1-6) for a 4-pole stator. The direction of rotation can be made anticlockwise by reversing the switching sequence (6-5-4-3-2-1). Thus the direction of stator phase currents at any given instance determines the position or orientation of stator poles. To reduce the torque pulsation and losses, the locus of the rotating magnetic field must be circular in nature. To achieve this, stator current must be sinusoidal with minimum amount of harmonic distortion. Therefore, reference voltage of the inverter is always sinusoidal. However, inverter output voltages are square wave at six step mode, which makes locus of the rotating magnetic field hexagonal in nature. SPWM technique is used to reduce the harmonics contains in output voltages and makes the stator current sinusoidal with minimum amount of harmonic distortion.

Table-1 Switching States of MOSFETs

Sequence No.	Polarity of Each Stator Coils			MOSFETs ON
	A	B	C	
1	+	-	+	M1, M5, M3
2	-	-	+	M4, M5, M3
3	-	+	+	M4, M2, M3
4	-	+	-	M4, M2, M6
5	+	+	-	M1, M2, M6
6	+	-	-	M1, M5, M6

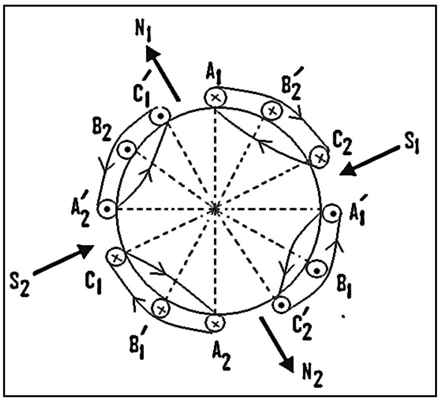

Fig. 6 Stator poles Orientation for Sequence-1

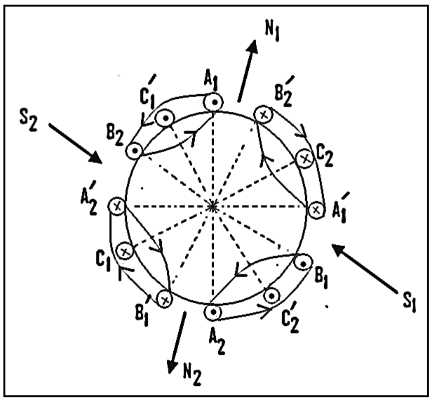

Fig. 7 Stator poles Orientation for Sequence-2

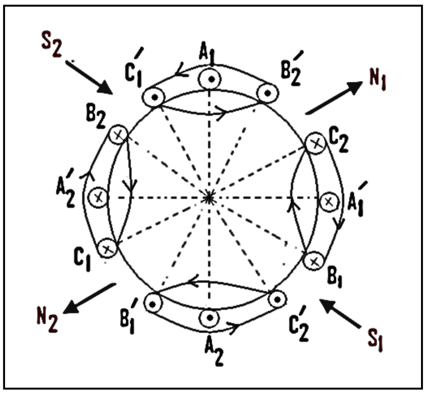

Fig. 8 Stator poles Orientation for Sequence-3

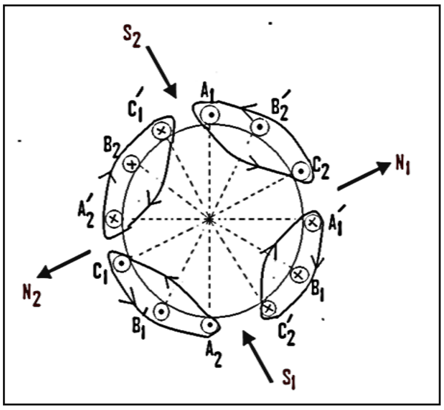

Fig. 9 Stator poles Orientation for Sequence-4

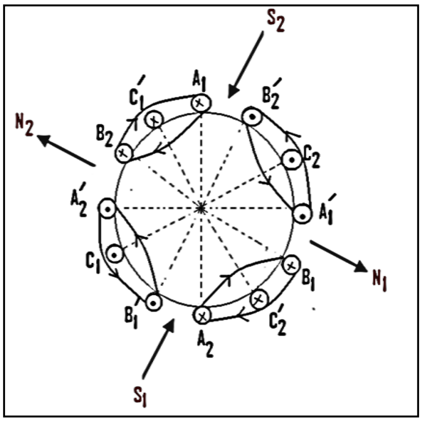

Fig. 10 Stator poles Orientation for Sequence-5

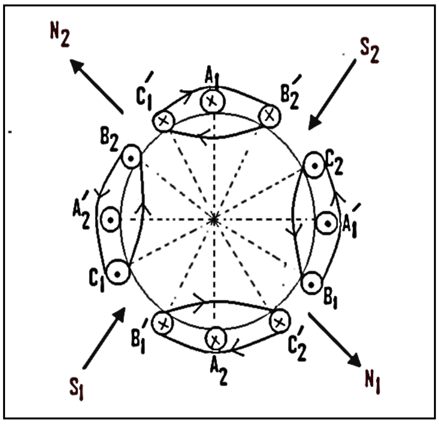

Fig .11 Stator poles Orientation for Sequence-6

Fig. 12 Experimental Setup

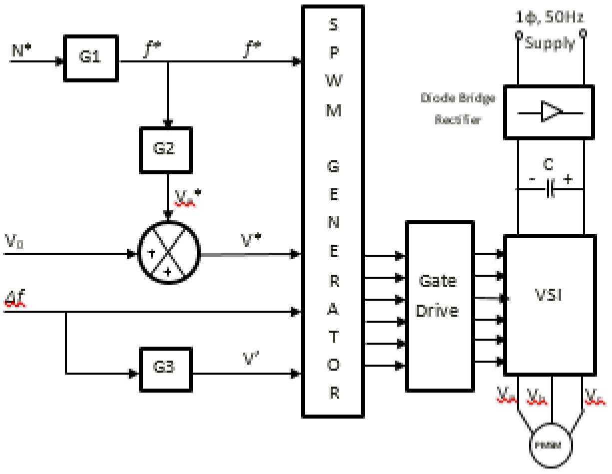

Fig. 13 Block Diagram of Control Scheme

DRIVE HARDWARE DESCRIPTION

The overall experimental setup is shown in fig.12. The drive hardware consists of a diode bridge rectifier and MOSFET based three phase voltage source inverter (VSI). The motor used here is a sinusoidal PMSM with non-salient pole rotor structure. Stator consists of 3-phase 4-pole star connected distributed winding of 220V rating. The Inverter is controlled by a Microchip's PIC18F series microcontroller based digital controller.

A resistive potentiometer is used to provide an analog input (0-5V dc). This reference input is connected to an analog input channel of the controller. The given analog input in turn determines the reference speed. There are also three selector switches, connected to digital input channels of the controller. According to the 3-bit input of these digital switches, a particular value of $\Delta \boldsymbol{f}$ is selected among eight predetermined values. An optical encoder is used to measure the motor speed. A Belt-pulley arrangement is used for the mechanical loading.

Control Scheme

The block diagram of the control scheme is shown in fig.13. During start, the controller reads the reference speed (N^*) and rate of change of frequency ($\Delta \boldsymbol{f}$) as inputs and calculates the values of reference frequency (f*) and rate of change of voltage ($\Delta \boldsymbol{V}$) using following equations.

$$\mathrm{f}^* = \frac{120\mathrm{N}^*}{\mathrm{P}} \tag{1}$$

$$\Delta V = \frac{(V_r - V_0)}{(f_r - f_0)/\Delta \boldsymbol{f}} \tag{2}$$

Where, f_r, V_r are rated frequency and voltage respectively. V_0 is the boost voltage to overcome stator resistance drop, f_0 is the starting frequency.

For any non-zero values (within specific range) of f* and Δf the inverter frequency (f) and Voltage (V) are set equal to f_0 and V_0 respectively. After completion of one electrical cycle, inverter frequency (f) is compared with the f*. If inverter frequency (f) is less than reference frequency, then inverter frequency and voltage are increased by Δf and ΔV respectively and it will continue until f becomes equal to f*. Now at any point of time, reference frequency is decreased to decrease the speed. The inverter frequency is decreased by Δf after each electrical cycle until f becomes equal to reference frequency. Now to determine the optimum value of Δf and ΔV, PMSM is started from zero speed with minimum value of Δf for a fixed reference frequency and it's observed whether the motor can reach the reference speed without losing its synchronism or not. The acceleration time can be calculated from the speed response. After that motor reference frequency is decreased to zero to decelerate the motor to zero speed and the machine performance is observed. This process will be carried out for an increased value of Δf. The performance (synchronism and acceleration/ deceleration) of the motor under test can be observed for different value of Δf. With the increase of Δf motor transient time decreases i.e. acceleration/ deceleration will increase. However, there will be a maximum value of Δf after that any further increase in Δf causes the loss of synchronism at a speed less than reference speed. The maximum value Δf and corresponding value of ΔV is the optimum value of these variables for the motor. Once the optimal value of Δf is determined, the machine will always operate with this value of Δf. Now to solve the starting problem whenever the stop comment is given the controller reference input become zero. However, the motor will not stop instantaneously, rather the controller decreases the voltage magnitude and frequency gradually using the optimal value of rate of change of frequency (Δf).

Implementation

Sinusoidal PWM technique is used to generate harmonically optimal variable voltage variable frequency supply. The control scheme is implemented using a PIC microcontroller based digital controller. Voltage is varied by varying the modulation index (M) from 0.05 to 0.9 (Avg. DC Voltage is =200 V (approx.). A Potentiometer is used to provide the analog reference input signal (0-5V dc) corresponding to a reference speed range of 0-1500 rpm or a frequency range (0-50Hz). The ratio between carrier frequency and reference frequency i.e. frequency modulation index taken here is 72. Accordingly sinusoidal reference wave is sampled at every 5° electrical angle and sampling time (T_s) is calculated as

$$T_s = 1 \times 10^3/(f \times 72) \tag{3}$$

At starting, the frequency (f) and modulation index (*M*) are set to 1Hz and 0.05 respectively. However, the final steady state value of the frequency (*f*) and modulation index (M*)* depends on the reference input (0-5 V dc). The ON time (T_m) of each MOSFET for one sampling time can be calculated using the following equations.

$$T_{m1} = T_s \times M \times \sin\theta\ ;\ \ T_{m4} = T_s - T_{m1} \tag{4}$$

$$T_{m2} = T_s \times M \times \sin(\theta - 120°)\ ;\ T_{m5} = T_s - T_{m2} \tag{5}$$

$$T_{m3} = T_s \times M \times \sin(\theta + 60°)\ ;\ \ T_{m6} = T_s - T_{m3} \tag{6}$$

Where the sign of the 'sine' term determines which switch will be 'ON' first. For example, during first sampling instant (i.e. $\theta = 5°$) $\sin\theta\ and\ \sin(\theta + 60°)$ are positive and $\sin(\theta - 120°)$ is negative so M1, M3 and M5 (sequence-1) will be ON first. The MOSFETs M4, M2 and M6 will be ON after T_{m1}, $T_{m5}$and T_{m3} time respectively. For the next 5° ($\theta = 10°$), the same procedure is used to calculate$T_{m1}\ toT_{m5}$. After completion of 360° rotation (one cycle) of the reference wave, VSI frequency (f) is compared with reference frequency (f^*). If f^*>f, the frequency is increased by $\Delta\boldsymbol{f}$ and the modulation index is increased by ΔM and it continues until f becomes equal to f^*. The rate of change of modulation index (ΔM) is calculated as,

$$\Delta M = \frac{1 - M_0}{(f_r - f_0)/\Delta\boldsymbol{f}} \tag{7}$$

Now if the reference frequency is decreased to reduce the speed i.e. f^*<f, the controller decreases the frequency and modulation index by $\Delta\boldsymbol{f}$ and ΔM respectively in every cycle until f becomes equal to f^*. As the motor transient response depends on the rate of change of frequency ($\Delta\boldsymbol{f}$), the provision for selection of different value of $\Delta\boldsymbol{f}$ is there. The status of the three I/O pins (binary input) determines the eight different values of $\Delta\boldsymbol{f}$ from 0.06 to 0.48. Any value of $\Delta\boldsymbol{f}$ can be selected through appropriate input pattern. During the entire speed range as the motor is always synchronized with the stator magnetic field, the motor speed is solely determined by the inverter frequency (f).The gate pulse waveforms for MOSFETs 1 and 4 are shown in fig. 15. The flowchart of the microcontroller program is shown in fig.14.

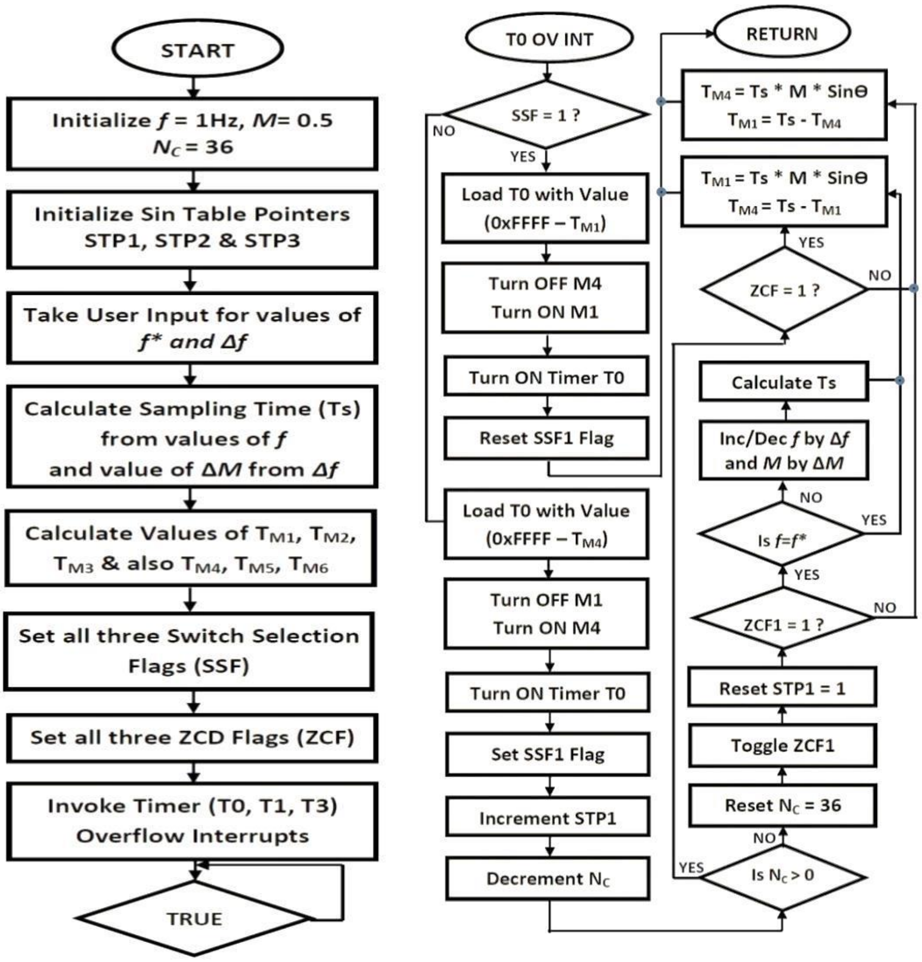

Fig. 14 Initialization and SPWM Generation Flowchart

EXPERIMENTAL RESULT AND DISCUSSION

At first the motor is accelerated form standstill to rated speed with different (increased) values of $\Delta\boldsymbol{f}$ for determination of optimal value $\Delta\boldsymbol{f}$. The speed responses for reference speed 750 rpm is shown in fig.16 for different values of $\Delta\boldsymbol{f}$ (0.12-0.48). It can be observed form the fig.17 that the acceleration time decreases with the increase in $\Delta\boldsymbol{f}$. However if the value of $\Delta\boldsymbol{f}$ is increased beyond 0.42 Hz/cycle i.e. 0.48Hz/cycle for reference speed is 750rpm ($f^* = 25Hz$), motor lost synchronism approximately at 600 rpm. So the threshold value of $\Delta\boldsymbol{f}$ is 0.42Hz/cycle in this case. The Motor terminal voltage is also varied proportional to the frequency to keep the flux linkage constant. After determination of $\Delta\boldsymbol{f}$**,** the machine is operated with step input as reference speed (750 rpm). The reference signal is applied for 19 second and then kept zero for 20 second. After this the signal is applied again. The response is shown in fig. 17. It can be observed from the response that the reference input is a step signal but controller changes the inverter output voltage and frequency as ramp signal with optimal value of **Δ*f (0.42Hz/cycle)*** to overcome the loss of synchronization problem. The speed response shows reverse rotation at the first time start. The rotor is intentionally kept in such a position so that the temporary reverse rotation can be observed at the first time starting. After reaching the steady state speed, the motor is stopped by applying the control deceleration process as discussed in Sec-II. Due to this process the angle between the rotor and stator position becomes zero at standstill and the starting process becomes smooth for the second time starting. Also note that as the motor is a synchronous motor, steady state speed is only determined by VSI output frequency. Steady state line current waveforms are shown in fig.18 and fig.19. Implementation of SPWM has made the nature of the current waves near to sinusoidal. The experimental result shows that the performance of proposed PMSM drive is satisfactory.

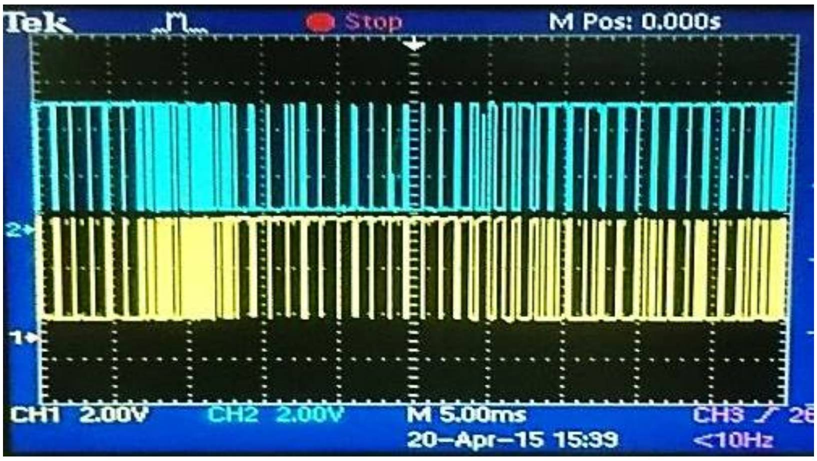

Fig.15 Gate pulse of M1 and M4

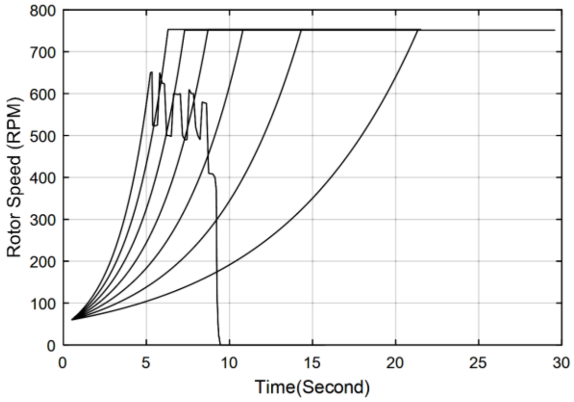

Fig.16 Speed response for reference frequency (f* = 25Hz) and different values of Δf ((0.12-0.48)

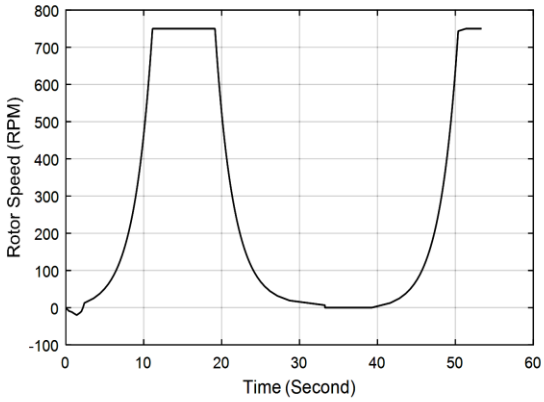

Fig. 17 Speed response for a step reference speed (750rpm) applied for 19 Sec. and remains zero for 20 Sec. & again applied at 39th Sec

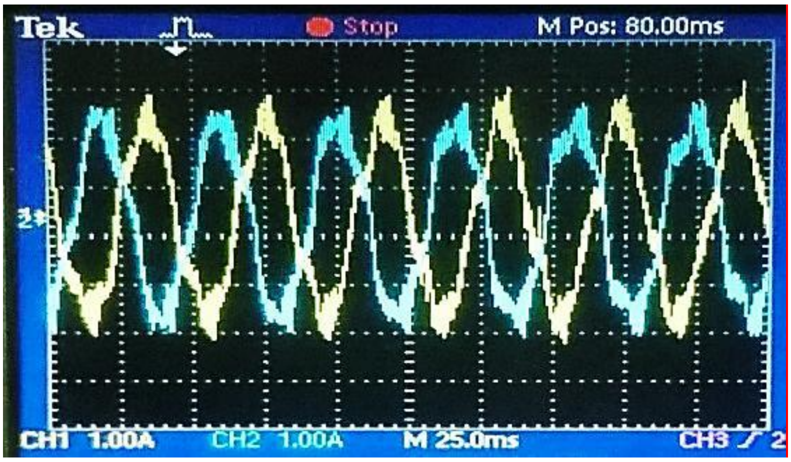

Fig. 18 Current waveforms of phase A and B

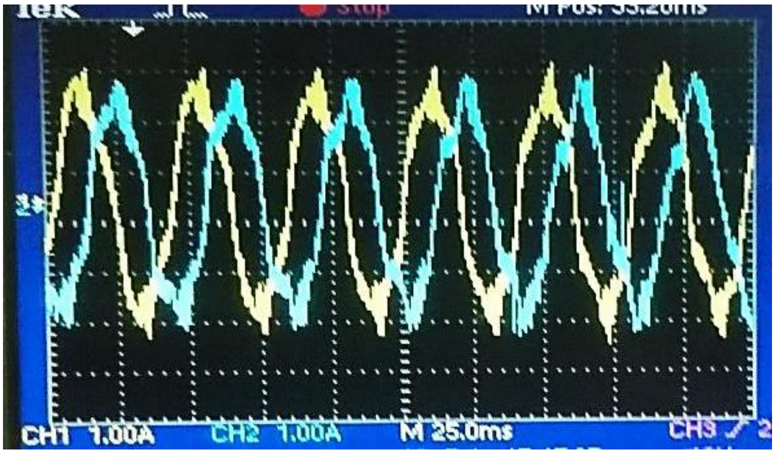

Fig. 19 Current waveforms of phase B and C

CONCLUSION

A simple low cost sensor-less open loop speed control technique for PMSM drive has been developed and exemplified in real time. The control technique ensures effective speed control performance and smooth starting with easy hardware implementation. A SPWM based simple algorithm is developed to implement the control scheme using the general purpose 8-bit microcontroller. The simple structure of the drive reduces the implementation cost compared to other control technique. The cost effectiveness, simplicity and high efficiency make the proposed drive a preferred one for the applications like fan, blower, pumps, air-condition and refrigeration system where the load torque is predictable and high dynamic performance is not required.

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