# An Efficient Flux Weakening Control Strategy of a Speed Controlled Permanent Magnet Synchronous Motor Drive for Light Electric Vehicle Applications

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***Abstract*—In this proposed work an efficient flux weakening control strategy of a four quadrant speed controlled Surface Mounted Permanent Magnet Synchronous Motor drive is presented. Permanent magnet synchronous motors are extensively used in light electric vehicle applications because it has large power density, high torque to inertia ratio, lower excitation losses and higher efficiency. In this proposed concept for speed controlled drive PWM current controller and PI speed controller is taken into consideration. For the implementation of such flux weakening control scheme a vector controlled surface mounted PMSM drive is established. It is emphasized that demagnetizing component of the d-axis current is introduced into the stator current. Therefore the proposed approach establishes better dynamic as well as steady state drive performance for high speed and energy efficient light electric vehicle applications. Hence a novel and efficient flux weakening control strategy is achievable.**

***Keywords—Flux weakening operation, Permanent magnet synchronous motor (PMSM), light electric vehicle, PWM controller, Speed controlled drive***

## I. INTRODUCTION

The invention of electrical vehicle is a promising and efficient approach for individual and urban transportation due to the fuel energy resources exhaustion and society concern. Due to the limited life-span of batteries, electric motors for automotive applications are normally fabricated to optimize the energy efficiency with a reduced volume [1-3]. Due to the advancement of permanent magnet materials and concept of modern converter technologies along with some sophisticated control algorithm permanent magnet synchronous motors are extensively used in automobile applications. Ideally, in a Permanent Magnet Synchronous Machine the features of air gap flux density distribution and voltage generated in the stator windings supplied by the permanent magnet material employed generates sinusoidal waveforms [4]. In the flux-weakening region while the inverter voltage is maintained, various control algorithms have been proposed to obtain the desired torque-speed performance. With the corresponding optimum dc link voltage and consequently the maximum input voltage and rated torque, the machine attains a speed termed as the base speed [5-6]. Beyond this speed the emf induced will cross the maximum applied voltage which in turn makes the phase current of the machine impractical. To conquer this circumstance, the induced emf must be less than the applied voltage by weakening the air gap flux linkages. The mutual air gap flux linkage is the product of the rotor and the stator flux linkages. This proposed process of flux weakening control is analogus to the flux-weakening technique normally done in the separately excited dc machine [7].

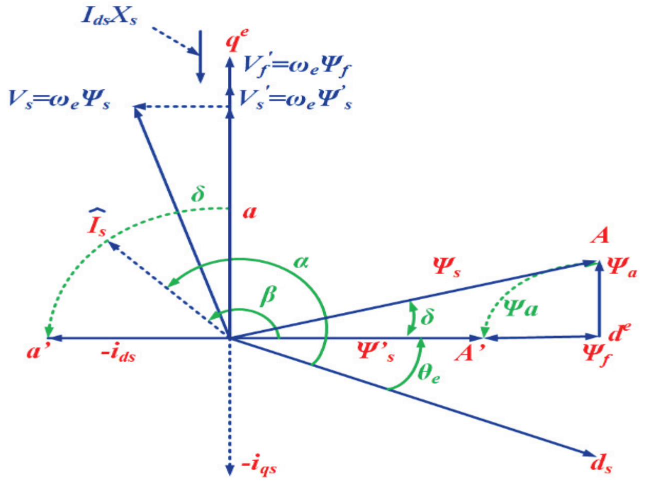

Fig. 1. Phasor diagram of a PMSM drive during flux weakening.

Permanent magnet synchronous machines (PMSM) have a major impact in a wide variety of industry applications, particularly the hybrid electric vehicle technology for their high power density, high torque-weight ratio and fast torque-speed or dynamic response. However both interior as well as surface mounted PMSMs have been employed for EV traction drives. Moreover interior PMSM is suitable for EV propulsion system as they can offer higher reliability and overload ability than surface mounted PMSM [8-9]. In case of electric vehicle traction applications a large speed range is mostly advantageous. Since no magnetization current is required for establishment of air-gap flux therefore PMSM imparts a high overall efficiency in the normal speed operating region. The permanent magnet synchronous machine possess the high power density which enhances the torque/weight/volume ratio even in the assembling space of a vehicle‘s engine compartment [10]. By weakening the flux PMSM attains a high speed and improved efficiency in a well defined speed range.

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Due to this reason PMSM can be best suited for light electric vehicle applications. Moreover, the selection of the machine type is based upon the type of control strategy used in light electrical vehicle [11-12]. It is shown in Fig. 1 that speed of a sinusoidal surface mounted permanent magnet synchronous motor can be controlled beyond base speed control. It is also described that because of armature reaction effect field weakening speed range is small in case of PMSM drive.

## II. IMPLEMENTATION OF FLUX-WEAKENING CONTROL SCHEEME FOR SPEED CONTROLLED PMSM DRIVE

In this proposed work a speed controlled PMSM drive system is incorporated for the establishment of flux weakening operation. For the sake of simplicity a basic torque controlled PMSM drive is considered having an outer control loop of speed for speed regulation of the proposed machine. The systematic block diagram representation of the proposed speed controlled drive system is depicted in Fig. 2. The dotted portion in this proposed block diagram represents the vector controller part. Vector control is sometimes also called de-coupling control or field oriented control. By the establishment of vector control in PMSM drive, independent control of flux and torque is obtained through the input in stator excitation [13-14].

To achieve the desired speed of the machine, mutual flux linkage is taken into account. Until and unless the magnitude of induced emf can't be greater than the dc bus voltage of the inverter, the proportion of induced emf to the stator frequency maintain a constant which in turn helps to keep fixed mutual flux and optimum frequency within the prescribed limit known as base speed [15-16]. In flux weakening mode of the drive system to adjust the current control beyond the induced emf magnitude the mutual air gap flux linkage can be settled to reduce in inverse proportion to the speed so that induced emf is fixed at a level corresponds to the base speed even though speed is impelled beyond that limit [17-18]. This control strategy is known as flux weakening strategy. Therefore the magnitude of torque cannot be supported to the base level that signifies to the base speed whose product generates the basic air gap power. Here in this discussion a simple speed controlled drive system is represented which considers the stator current reference producing electromagnetic torque obtained from the torque reference. Therefore as an outcome mutual d-axis flux linkages have been added with the main air-gap flux linkages and d-axis flux linkage which generates the stator current magnitude [19].

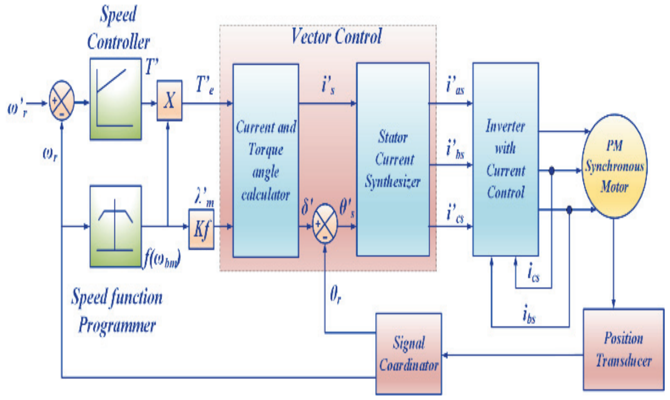

Fig. 2. Systematic Block diagram representation of a speed-controlled PMSM drive.

The magnitude of q- and d-axis armature currents can be represented through the transformation matrix in the rotor reference frame as

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t - \frac{2\pi}{3}\right) & \cos\left(\omega_r t + \frac{2\pi}{3}\right) \\ \sin\omega_r t & \sin\left(\omega_r t - \frac{2\pi}{3}\right) & \sin\left(\omega_r t + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{1}$$

The representation of stator currents in the rotor reference frames have been summarized as

$$\begin{bmatrix} i_{qs}^r \\ i_{ds}^r \end{bmatrix} = i_s \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \tag{2}$$

By establishing the stator flux current component is zero while maintaining the torque angle zero electromagnetic torque can be substituted as

$$T_e = \frac{3}{2}.\frac{P}{2}\lambda_{af} i_{qs}^r = \frac{3}{2}\frac{P}{2}\lambda_{af} I_s \tag{3}$$

The q and d- axes voltages in rotor reference frames in steady state are represented as

$$v_{qs}^r = \left(R_s + L_q p\right)I_s + \omega_r\lambda_{af} = R_s I_s + \omega_r\lambda_{af} \tag{4}$$

$$v_{ds}^r = -\omega_r L_q I_s \tag{5}$$

A PWM current controller is chosen for the performance validation. At the time of standstill condition having positive speed command, the reference torque is applied to a positive maximum till the actual speed meets the speed reference. While rotor speed and the reference speed matches torque reference reduces to catch up the load torque and the corresponding friction torque. Torque reference is kept to negative while speed reference switches from positive to negative values which in turn speed of the motor falls to zero value. Keeping the negative torque rotor is supposed to rotate in opposite direction and tries to meet the speed reference. While it reaches at negative value the electromagnetic torque is reduced [20-21].

## III. PEFORMANCE EVALUATION DURING FLUX WEAKING OPERATION OF A SPEED CONTROLLED SMPMSM DRIVE

The entire performance of a multi quadrant speed controlled PMSM drive is established here during flux weakening operation. The dynamic behaviour of drive system is evaluated by incorporating by torque producing stator current reference determined from torque reference. In this proposed work direct axis mutual flux linkage is taken as reference in rotor reference frame. For the determination of drive performance during flux wakening operation PWM current controller is chosen and PI speed controller is taken into consideration. The complete process flow diagram for the evaluation of four quadrant speed controlled drive performance is depicted in Fig.3.

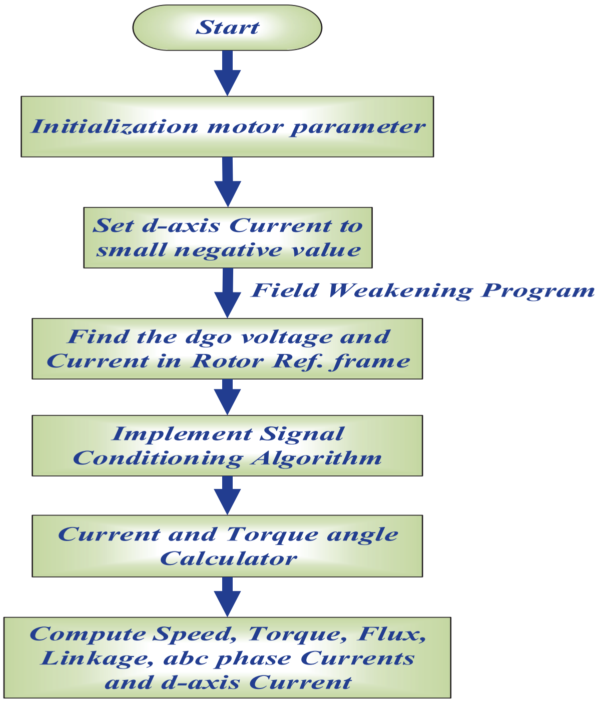

Fig. 3. Complete process flow diagram for implementing flux weakening operation of a speed controlled PMSM drive.

It is observed that the machine is at standstill condition at the time of starting with a positive speed command and corresponding torque reference reaches to positive maximum until the actual speed matches with the command speed. In this proposed concept d-axis reference current is decreased during flux weakening which in turn a reduction of air gap flux linkages. In Fig. 4 the speed of the drive system under flux weakening operation is depicted.

While the actual speed of the machine passes to negative value electromagnetic torque is decreased faintly as compared to the positive load torque. Therefore torque profile of drive reaches to negative value until speed changes to negative command. Hence rotor eventually slows down to zero speed. In Fig. 5 Electromagnetic torque behaviour during flux weakening operation is presented. It is noticeable from the torque response that at 0.02 sec flux weakening operation is initiated and continued until the machine speed tries to reach to the steady value to fix the air-gap power.

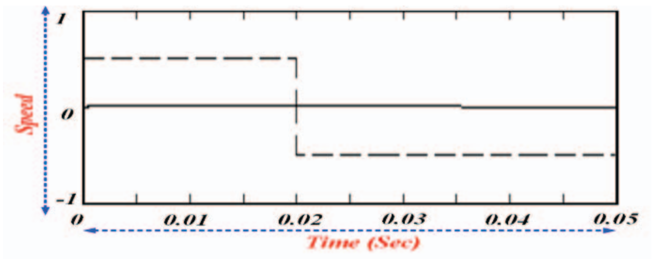

Fig. 4. Electrical Speed vs time response during flux-weakening.

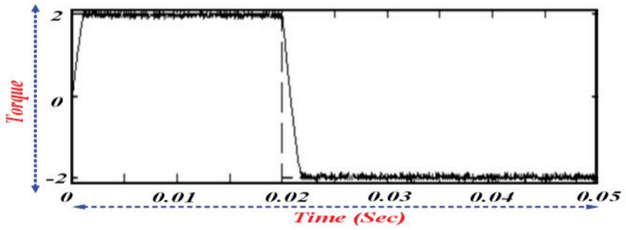

Fig. 5. Electromagnetic Torque vs time response during flux-weakening

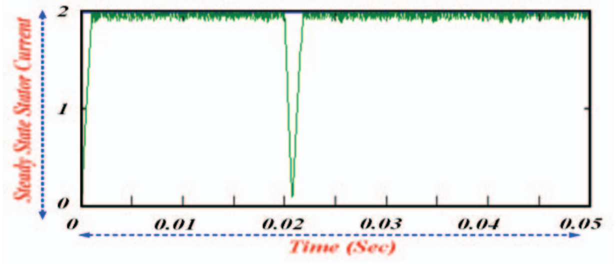

Fig. 6. Steady state stator current vs time response during flux-weakening.

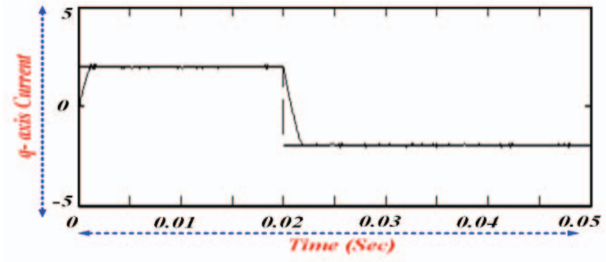

Fig. 7. q-axis reference current vs time response during flux-weakening.

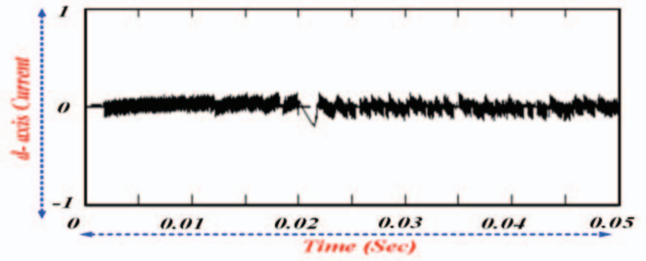

Fig. 8. d-axis reference current vs time Response.

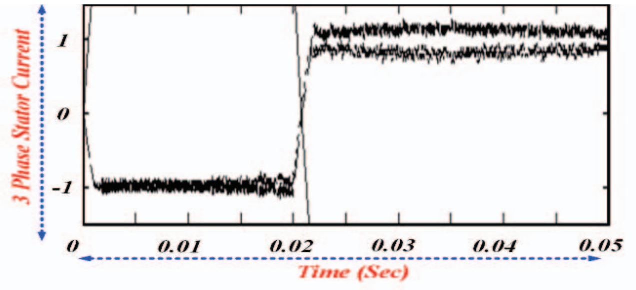

Fig. 9. Phase currents vs time response during flux-weakening.

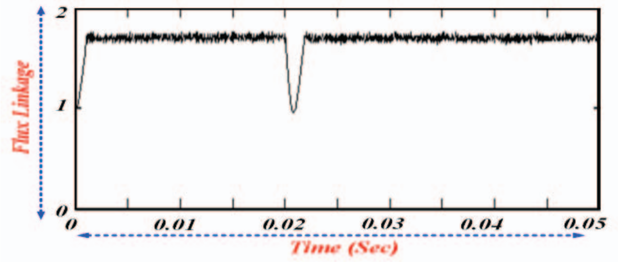

Fig. 10. Flux Linkage vs time response during flux-weakening.

The steady-state stator current response during flux weakening operation of the speed controlled PMSM drive is shown in Fig. 6. It can be described in the sense is that during flux weakening stator current magnitude is reduced to zero value at some specific point and after some instant current tries to maintain the steady pattern having little ripples.

The quadrature axis reference current i.e. the torque producing component of the stator current during flux weakening operation is shown in Fig. 8. Similar behaviour of drive system like electromagnetic torque is initiated in Fig. 7. For the determination of dynamic performance of a four quadrant speed controlled PMSM drive the reference d-axis current, reference 3-phase currents and the mutual flux linkage during flux weakening mode is also represented in Fig. 8, Fig. 9 and Fig. 10 respectively.

In Fig. 8 d-axis current response during flux weakening operation is represented. The variation of d-axis current i.e. flux producing component of the stator current is also reduced at 0.02 sec i.e. during weakening of the main flux which results in the increase in speed of the machine. Therefore after flux weakening operation machine tries to attain the steady state value.

Variation of 3-phase armature current during flux weakening operation is represented in Fig. 9. In the similar manner it is observed that while flux weakening mode starts multi-phase currents increase to meet with the steady-state value in order to meet the high performance of the machine.

In Fig. 10 flux linkage variation during flux weakening operation is represented. As flux linkage varies inversely to the speed of the machine, therefore it is observed that at 0.02 sec flux weakening operation initiates as a result high speed will be achieved which can be utilized to apply in light electric vehicles.

## IV. CONCLUSION

This paper significantly establishes an efficient flux weakening operation of a speed controlled PMSM drive in constant torque angle region. To achieve the desired performance of the drive system during flux weakening operation torque reference is decreased to keep the air gap power constant. In this proposed established strategy the magnitude of electromagnetic torque is maintained by the incorporation of signal conditioning circuit and speed controller output. In light electric vehicles this flux weakening control technique is efficient and advantageous because of smaller weight, high power density, stable torque-speed curve, high efficiency, simple control circuit etc. Future extension of the proposed concept can be implemented in real-time environment to meet the desired goal.

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