CHAPTER 1

INTRODUCTION

1.1 Motivation

Due to the merits of high efficiency, high power density, high torque to inertia ratio and free from maintenance, surface-mounted permanent magnet synchronous motors (SMPMSM) have now been widely adopted for servo drives in various applications, such as robotics, manipulators, machine tools and production materials handling [1,2]. To achieve both fast dynamic response and high performance for four-quadrant operation, a vector control is usually used in the SMPMSM drives. When the synchronous rotating d-axis is in alignment with the direction of the north pole of the rotor permanent magnet, the developed torque depends only on q-axis current due to the non-salient property of the SMPMSM. Therefore, some different control strategies were proposed to achieve some predefined performance index by the control of d-axis current [3]. However, the zero d-axis current control is the most popular method used in industrial applications due to its easy implementation and the achievement of maximum torque per ampere control. Hence, the control strategy of zero d-axis current control is adopted for the torque control when the drive is operated on constant torque limit region. In spite of the above advantages, the required stator voltage may exceed the capacity of the inverter when the rotor speed exceeds some rated value [4]. Thus, to take full advantage of the capability of the drives, information of the constraints of the SMPMSM drives is important to the controller design in the case that the rotor speed exceeds some rated value.

The extension of the speed operation range is made by the field weakening control strategy such that the SMPMSM drive can be operated over wider speed range than that of $i_{ds} = 0$ control strategy. In addition, a robust field weakening control strategy is necessary for the high performance operation of the drives when considering the variations of dc link voltage and parameters. Improvement of the existing field weakening control strategy is also required to eliminate the gradual adjustment by feedback mechanism to achieve faster response and better stability. From the view of high performance drives, high efficiency operation is also an important topic for the robust field weakening control strategy.

To keep high performance operation of the drives, different approaches were proposed to mitigate the disturbances. Some robust control methods were proposed to achieve a high performance operation [19-42]. Among them, sliding-mode control (SMC) has received growing research interest due to their good features, such as fast dynamics, parameter insensitive and good disturbance rejection ability. For simplicity, the design of the above controllers is often based on the assumption that the inverter is considered as an ideal current amplifier. However, this assumption can be guaranteed only when the output saturation bounds of the controller are consistent with their true values. These controllers would not function properly in field weakening operation mode since the maximum available torque is varied with the variation of rotor speed and parameters of the drives. Moreover, by using the sliding-mode control strategy, the resultant chattering and additional control energy for the reaching mode condition also impose restrictions on the proper field weakening operation of the drives. In view of above problems, the motivation of this dissertation is trying to find a robust controller for SMPMSM drives to overcome the above disadvantages.

1.2 Literature Survey

The operational limitations of the PMSM for variable speed drives have been studied extensively in many literatures [7,8,63,64]. The relation between the parameters of PMSM and the curve of maximum torque vs. speed is investigated in [64]. In [7,8], the operation limits of PMSM based on constant power criterion is studied. Three types of phase current control, namely zero d-axis current, unity power factor and constant mutual flux linkages for PMSM were discussed in detail in [9].A comparison between zero d-axis current and maximum torque per ampere for an interior PMSM is provided in [10], where the maximum torque per ampere is superior to zero d-axis current was concluded therein.

In order to effectively extend the operating speed range, many field weakening controls were proposed [4,8,10-14]. Some field weakening control methods calculate the desired current commands based on the accurate model parameters to achieve fast dynamic response and/or better efficiency [4,8,10,11]. However, the resulting performance will deteriorate when the model parameters are varied with different operating conditions. Hence, to overcome this disadvantage, several robust field weakening control methods were proposed to achieve a robust drive [12-14]. In [12], a field weakening method was proposed by letting the d-axis current command be proportional to the q-axis current error to obviate the use of the exact motor parameters. However, the need of the existing torque error to generate the desired d-axis current may result in unstable operation of the drive system [13,14]. As in [13], another method is proposed by adjusting the d-axis current command as well as the upper/lower bounds of the maximum q-axis current of the speed controller through a proportional-integral (PI) controller of the error between the maximum inverter output voltage and the output voltage resulting from the d- and q-axes current PI controllers. However, it is found that the corresponding q-axis current bounds under transient condition can not follow the true bounds instantaneously. Basically, the d-axis current command is fixed at the beginning of the transient such that the q-axis current bound can be gradually adjusted by the PI controller. As the d-axis current is adjusted by the PI controller, the corresponding q-axis current bound is also calculated simultaneously. In fact, the same method was applied to the interior permanent magnet synchronous motor drives [15] and the induction motor drives [16]. However, as pointed out by [17, 18], the PI voltage controller of [13] should be replaced by an integral (I) controller to either ensure the drive stability or simplify the controller design. The proposed robust field weakening control of [14] is similar to that of [13] except replacing the PI voltage controller with an integral controller together with an additional modification of the d-and q-axes current commands based on checking the constraint of the voltage bound, where the resulting dynamic response can be somewhat improved.

Some other studies were focused on the control design for a robust current [19-24] or speed [25-33] or position [34-42] controllers to achieve a high performance operation. Furthermore, a load torque observer is proposed to estimate the inaccessible load torque and then the estimated load torque is fed to the controller to upgrade the robustness of the drive system [43-47]. Among them, variable-structure control or sliding-mode control are often adopted for robustness features. Due to the resultant chattering phenomenon in the sliding-mode control, some methods were proposed to reduce the chattering phenomenon [48-54]. A load torque observer is proposed to relax the requirement on the upper bound of the lumped uncertainty [56, 57]. As in [55], the limitations for the practical implementation of a sliding-mode speed controller are discussed. However, due to the limitation of maximum available torque in the field weakening region, there are very few literatures dealing with the SMC operated in the field weakening region for the SMPMSM drive.

1.3 Contributions of the Dissertation

Basically, the research objectives of this dissertation are focused on a robust control strategy for a variable speed SMPMSM drive system. First, a reasonable classification of operation regions for a four-quadrant drive operation and the profound effects due to the consideration of the stator resistance are shown. Second, to fully exploit the torque capability as well as to achieve minimum copper loss operation for SMPMSM drives, a robust field weakening control strategy is proposed. Third, based on the robust field weakening control strategy, an adaptive SMC speed controller is proposed to obtain a high performance operation. The major contributions of the dissertation can be summarized as follows:

First, the classification of ten operation regions for four-quadrant operations and the partial field weakening concept are proposed. It is seen that consideration of the stator resistance is crucial to achieve the fastest response.

Second, a closed form solution of the maximum available torque-producing current is proposed for calculating the corresponding saturation bounds of the speed controller in real time. By combining the closed form solution and a conventional PI speed controller, the drive can achieve both fast response and automatic field weakening control.

Third, a robust tuner based on the proposed virtual maximum phase voltage amplitude together with a minimum copper loss controller based on the partial field weakening concept is proposed to achieve minimum copper loss over the entire operating range. Moreover, a dc link voltage sensorless control version is also proposed which is very useful in electrical vehicle applications. Due to the application of the robust tuner, these good performances can be achieved in spite of the variations of the dc link voltage and the parameters of the SMPMSM.

Fourth, a sliding-mode speed controller with an adaptive lumped uncertainty observer is proposed to achieve the robust control aim. A tighter estimation of the lumped uncertainty is obtained by applying the adaptive lumped uncertainty observer to fully exploit the maximum torque capability as well as to reduce the chattering phenomenon. Due to these advantages, the proposed sliding-mode speed controller may be used to replace the PI speed controller to achieve high performance operation for SMPMSM drives in the near future.

1.4 Outline of the Contents

The contents of this dissertation can be outlined as follows:

In chapter 2, the mathematical model and constraints of the SMPMSM drives are first reviewed briefly. Then, the classification of operation regions for four-quadrant operation is presented. Also, the profound effects resulted from the consideration of the stator resistance is clarified here. Finally, the main torque control strategies for PMSM drives operated for lower than base speed are discussed briefly and some experimental results conducted by using a DSP-based prototype drive are given to verify the validity and limit of the torque control strategy of zero d-axis current. Additionally, other experiments are conducted to demonstrate the classification of ten regions for four quadrant operation and to verify the effects of with neglecting stator resistance.

In chapter 3, the extension of the speed operation range is made by using the field weakening control strategy such that the SMPMSM drive can be operated over wider speed range than that of $i_{ds} = 0$ control strategy. First, a novel field weakening control based on a beautiful closed form solution of the available maximum torque is proposed to eliminate the gradual adjustment by feedback mechanism so as to achieve faster response and better stability. Next, the proposed robust field weakening control strategy is described in detail. Finally, some software simulations and experimental results conducted by using a DSP-based prototype drive are given to verify the validity of the proposed strategy.

In chapter 4, first, a sliding-mode speed controller with an adaptive strategy for estimating the lumped uncertainty is proposed to relax the requirement for the upper bounds of the lumped uncertainty. By combining the sliding-mode speed controller and the drive control strategy proposed in chapter 3, the conventional PI speed controller is replaced by the proposed sliding-mode speed controller. Therefore, the robustness of the proposed control strategy can be highly improved. Finally, some simulation and experimental results resulting from a DSP-based prototype drive are given to verify the validity of the proposed adaptive sliding mode speed controller.

Finally, some conclusions are made and some topics suggested for further research are given in the last chapter.