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PREDICTIVE SPEED CONTROLLER OF BLDC SYSTEM USING ADAPTIVE PIWITHDISTURBANCE COMPENSATION TECHNIQUES

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ABSTRACT

To optimize the speed-control performance of the Brushless D.C motor (BLDC) system without disturbances and uncertainties, a predictive nonlinear speed-control algorithm for the BLDC servo systems using Sliding-Mode Control (SMC) and disturbance compensation techniques are proposed. In order to overcome the chattering problem, Sliding Mode Reaching Law (SMRL) method is proposed. Thus, a composite control method combining an SMC part and a feed forward compensation part based on an Extended Sliding-Mode Disturbance Observer (ESMDO) is proposed to estimate lumped uncertainties and strong disturbances.. The adaptive compensation technique is additionally used, for observing the disturbance of the motor for improving accuracy. Finally to reduce the disturbances of the motor using ADAPTIVE and ESMDO control method is used efficiently. Simulation and experimental results show the validity of the proposed control approach

KEY WORDS--- Sliding Mode Reaching Law (SMRL), Adaptive Controller, Extended Sliding Mode Observer (ESMDO)

1. INTRODUCTION

In the Brushless D.C motor (BLDC) control system, the classical Proportional Integral (PI) control technique is still popular due to its simple implementation. However, in a practical BLDC system, there are large quantities of the disturbances and uncertainties, which may come internally or externally, e.g., unmodeled dynamics, parameter variation, friction force, and load disturbances. It will be very difficult to limit these disturbances rapidly if adopting linear control methods like PI control algorithm.

Therefore, many nonlinear control methods have been adopted to improve the control performances in systems with different disturbances and uncertainties, e.g., robust control,Sliding-Mode Control (SMC), adaptive control, back stepping control, predictive control, and intelligent control and so on. In these nonlinear control methods, SMC method is well known for its invariant properties to certain internal parameter variations and external disturbances, which can guarantee perfect tracking performance despite parameters or model uncertainties.It has been successfully applied in many fields. In the fuzzy sliding-mode approach was applied to a six-phase induction machine. In a hybrid terminal sliding-mode observer was proposed based on the nonsingular terminal sliding mode and the high-order sliding mode for the rotor position and speed estimation in one BLDC control system. The performance of a sliding mode controller was studied using a hybrid controller applied to induction motors via sampled closed representations.

However, the robustness of SMC can only be guaranteed bythe selection of large control gains, while the large gains will lead to the well-known chattering phenomenon, which can excite high-frequency dynamics. Thus, some approaches have been proposed to overcome the chattering, such as continuation control, high-order sliding-mode method, complementary sliding-mode method, and reaching law method. The reaching law approach deals directly with the reaching process, since chattering is caused by the nonideal reaching at the end of the reaching phase. In authors presented some reaching laws, which can restrain chattering by decreasing gain or making the discontinuous gain a function of sliding-mode surface. In a novel exponential reaching law was presented to design the speed- and current-integrated controller. To suppress chattering problem, system variable was used in this reaching law.

However, in the aforementioned reaching laws, the discontinuous gain rapidly decreases because of variation

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of the functions of the sliding surface, thus reducing the robustness of the controller near the sliding surface and also increasing the reaching time.

In order to solve the aforementioned problems, a novel reaching law, which is based on the choice of an exponential term that adapts to the variations of the sliding-mode surface and system states, is proposed. This reaching law is able to deal with the chattering/reaching time dilemma. Based on this reaching law, a sliding-mode speed controller of BLDC is developed. Then, to further improve the disturbance rejection performance of SMC method, Extended Sliding-Mode Disturbance Observer (ESMDO) is proposed, and the estimated system disturbance is considered as the feedforward compensation part to compensate sliding-mode speed controller. Thus, a composite control method combining an SMC part and a feedforward compensation part based on ESMDO, called SMC+ESMDO method, is developed

2. SLIDING MODE CONTROL

Sliding Mode techniques are one approach to solving control problems and thearea of increasing interest. This text provides the reader with an introduction to the sliding mode control area and then goes on to develop the theoretical results. Industrial case studies, which present the results of sliding mode controller implementations, and are used to illustrate successful practical applications of the theory.

In the formulation of any control problem there will typically be discrepancies between the actual plant and the mathematical model developed for controller design. This mismatch may be due to any number of factors and it is the engineer's role to ensure the required performance levels exist despite the existence of plant model mismatches. This has led to the development of so-called robust control methods. One particular approach to robust controller design is the so-called sliding mode control methodology which is a particular type of Variable Structure Control System (VSCS).

It is characterized by a suite of feedback control laws and a decision rule (termed the switching function) and can be regarded as a combination of subsystems where each subsystem has a fixed control structure and is valid for specified regions of system behavior. The advantage is its ability to combine useful properties of each of the composite structures of the system. Furthermore, the system may be designed to possess new properties not present in any of the composite structures alone. In sliding mode control, the VSCS is designed to drive and then constrain the system state to lie within a neighborhood of the switching function.

Its two main advantages are

(1)The dynamic behavior of the system may be tailored by the particular choice of switching function.

(2) The closed-loop response becomes totally insensitive to a particular class of uncertainty. Also, the ability to specify performance directly makes sliding mode control attractive from the design perspective.

A. Terms of sliding mode controler

Nonlinear system model imprecision may come from actual uncertainty about the plant (e.g., unknown plant parameters), or from the purposeful choice of a simplified representation of the system's dynamics. Modeling inaccuracies can be classified into two major kinds: structured (or parametric) uncertainties and unstructured uncertainties (or unmodeled dynamics). The first kind corresponds to inaccuracies on the terms actually included in the model, while the second kind corresponds to inaccuracies on the system order. Modeling inaccuracies can have strong adverse effects on nonlinear control systems.One of the most important approaches to dealing with model uncertainty are robust control. The typical structure of a robust controller is composed of a nominal part, similar to a feedback control law, and additional terms aimed at dealing with model uncertainty. Sliding mode control is an important robust control approach. For the class of systems to which it applies, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. On the other hand, by allowing the tradeoffs between modeling and performance to be quantified in a simple fashion, it can illuminate the whole design process.

Sliding Surfaces

This section investigates Variable Structure Control (VSC) as a high-speed switchedFeedback control resulting in sliding mode. For example, the gains in each feedback path switch between two values according to a rule that depends on the value of the state at each instant. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a prespecified (user-chosen) surface in

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the state space and to maintain the plant's state trajectory on this surface for subsequent time. The surface is called a switching surface. When the plant state trajectory is "above" the surface, a feedback path has one gain and a different gain if the trajectory drops "below" the surface. This surface defines the rule for proper switching. This surface is also called a sliding surface (sliding manifold). Ideally, once intercepted, the switched control maintains the plant's state trajectory on the surface for all subsequent time and the plant's state trajectory slides along this surface. The most important task is to design a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception. A Lyapunov approach is used to characterize this task Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let V(x) be a continuously differentiable scalar function defined in a domain D that contains the origin. A functionV(x) is said to be positive definite if V (0) =0 and V(x)>0 for x = 1. It is said to be negative definite if V (0) =0 and V(x)>0 for x =-1.

Lyapunov method is to assure that the function is positive definite, when it is negative and function is negative definite if it is positive. In that way the stability is assured. A generalized Lyapunov function, that characterizes the motion of the state trajectory to the sliding surface, is defined in terms of the surface. For each chosen switched control structure, one chooses the "gains" so that the derivative of this Lyapunov function is negative definite, thus guaranteeing motion of the state trajectory to the surface. After proper design of the surface, a switched controller is constructed so that the tangent vectors of the state trajectory point towards the surface such that the state is driven to and maintained on the sliding surface. Such controllers result in discontinuous closed-loop systems.

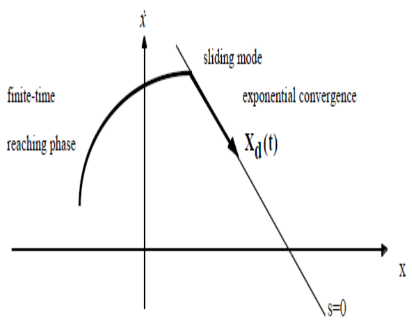

Figure1 Graphical Representation of Sliding Mode Reaching Law

Finally, satisfying (4.1) guarantees that if x(t=0) is actually off x_d(t=0), the surfaceS(t) will be reached in a finite time smaller than *s*(*t* = 0) / h. Assume for instance that's (t=0)>0, and let treach be the time required to hit the surface s=0.Integrating (4.2) between t=0 and treach leads to 0-s(t=0)=s(t= treach)-s(t=0) £-h (treach -0)which implies that treach £ *s*(*t* = 0) / h.The similar result starting with s(t=0)>0 can be obtained as treach £ s(t = 0) /h Starting from any initial condition, the state trajectory reaches the time-varying surface in a finite time smaller than s(t = 0) /h , and then slides along the surface towards x $_d$(t) exponentially, with a time-constant equal to 1. In summary, the idea is to use a well-behaved function of the tracking error, and then select the feedback control law U, in such thatS_2remains characteristic of a closed-loop system, despite the presence of model imprecision and of disturbances.

B. Design of SMC speed controller with proposed SMRL

The novel SMRL is realized based on the choice of an exponential term that adapts to the variations of the sliding-mode surface and system states. This reaching law is given by

$$S=eq(x_1, s).sgn(s)$$

$$eq(x_1, s)=k/[€+(1+1/|x_1|-€)e^{-\delta|s|} \quad (1)$$

Where k>0, δ >0, and 0 < ε <1,$x_1$is the system state. In this novel reaching law, it can be found that if |s|increases, theeq(x_1, s) converges to the value of k/εthat is greater than the value of *k*. This indicates that a faster reaching time can be obtained. On the other hand, if |s|decreases, denominator term of the eq(x_1, s) approaches 1+ 1/ |x_1|, then the eq(x_1, s) converges tok|x_1 in whichsystem state |x_1|gradually decreases to zero underthe control input designed in the next section. This indicates that when the system trajectory approaches the sliding-mode surface, the eq(x_1,s) gradually decreases to zero to suppress the chattering. Thus, the controller designed by proposed reaching law can dynamically adapt to the variations of the sliding-mode surface and system states |x_1| by making eq(x_1.s) vary between *k/ε* and zero.

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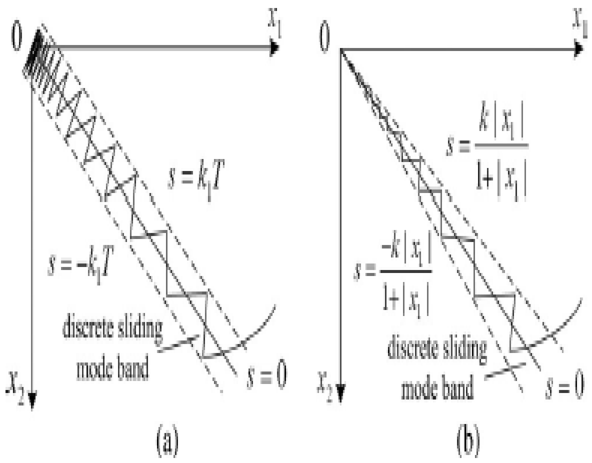

Figure2 State Trajectory of Equal Reaching Law and Novel Reaching Law
(a) Without reaching law (b) with reaching law

3. CONTROL CIRCUIT

The Terms of operation shown in the bockgiven below

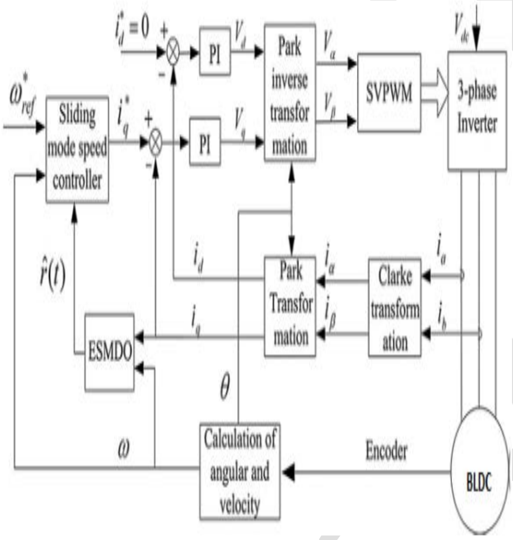

Figure3 Speed Control Circuit of BLDC

A. Speed Controller working based on the Proposed Reaching Law

Speed-control algorithms should keep the actual speed track of the speed reference ω_{ref}accurately under the occurrence of disturbances. To achieve this control objective, the tracking error is defined as e = ω_{ref}– ω. Then, according to aforementioned Sliding Mode Design method, the following sliding-modesurface is chose:

S = e = ω_{ref}– ω (2)

which is called linear sliding-mode surface.

Taking the time derivative of the sliding-mode surface yields

S= *ω*˙ ref − *ω*˙(3)

Moreover, according to the, the dynamic equation of the motor can be expressed as follows, with the parametersvariations taken into account.

ω=a I $_q$–c_n ω+r(t)(4)

where a = an +Δa = 3p2ψa/2J, b = bn +Δb = p/J, and c = cn +Δc = B/J. an , bn , and cnare nominal parameter. Δa, Δb, and Δc are parameter variations.

In , r(t) = Δaiq − Δcω − bTLrepresents the lumped disturbances including internal parameter variation, friction force, and external load disturbances, which is assumed to be bounded

|r (t) | ≤ l (5)

where *l* is the upper bound of the lumped disturbances

l-eq(x_1,s).sgn(s)(6)

However, it is difficult to select upper bound in practical application, because the lumped disturbances are difficult to know the exact value and measure. Though some methods, such as error control and trial, can be used to select upper bound, these approaches are time consuming and cannot provide enough robustness.

B.The Pi Controller Principle

PI controller is an algorithm that can be implemented without resorting to any heavy control theory. The aim of such an algorithm is to determine the plant input (in our case the stator voltage frequency) that will make the measured output (in our case the speed of the rotor) reach the reference (the speed the user wishes to have). PI stands for Proportional and Integral, two terms, which describe two distinct elements of the controller a proportional term, which is equal to the product of the error signal (the measured plant output subtracted to the reference), by a constant called the proportional gain. The proportional term mainly determines the short-term behavior of the controller since it determines how the controller strongly reacts to reference changes an integral term, which adds long-term precision to the controller.

This term is the product of the sum of all the previous error signal values by a constant called the integral gain. This sum keeps all the previous error signal values in memory, and evolves as long as the error is not zeroIt allows the controller to cancel the difference between the measured output and the

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reference, but it usually makes the closed loop system slower and decreases its stability. However, These two terms are sometimes added to a third one, proportional to the derivative of the error signal. The resulting regulator is then called a PID (Proportional, Integrator and Derivative). To control the speed of and induction motor by the V/f principle, this third term is not useful. It increases the speed of the closed loop, but it also derivates noises and it decreases the stability of the closed loop. So, the D term is tricky to adjust.

C.Adaptive Control

AdaptiveControlcoversasetoftechniques which providea systematic approachfor automaticadjustment ofcontrollers in real time, in order to achieve or to maintaina desired level of control system performance when the parameters of theplant dynamic model are unknown and/or change in time. Consider first the case when the parameters of the dynamic model of the plant to be controlled are unknown but constant (at least in a certain region of operation).In such cases, although the structure of the controller will not depend in general upon the particular values of the plant model parameters, the correct tuning of the controller parameters cannot be done without knowledge of their values. Adaptive control techniques can provide an automatic tuning procedure in closed loop forthe controller parameters. In such cases, the effect of the adaptation vanishes astime increases. Changes in the operation conditions may require a restart of theadaptation procedure. Now consider the case when the parameters of the dynamic model of the plant change unpredictably in time. These situations occur either because the environmental conditionschange or because we have considered simplified linear models for nonlinear systems.

These situations may also occur simply because the parameters of the system are slowly time- In order to achieve and to maintain an acceptable level of control system performance when large and unknown changes in model parameters occur, an adaptive controlapproach has to be considered. In such cases, the adaptation will operate most of the time and the term non-vanishing adaptationfully characterizes this type of operation (also called continuous adaptation)

$$\theta(t)= v(t), v(t)=u-a(\theta)/j-T_1 \; U=1/J \; T_{m, T1}=1/J \; T_1 \quad (7)$$

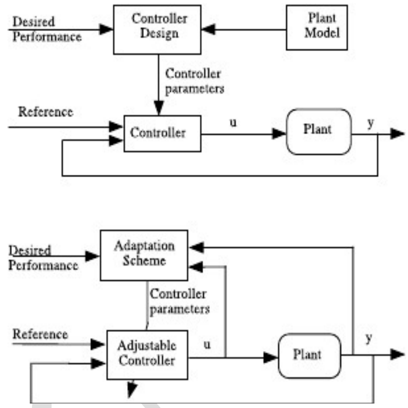

Figure 5 conventional and adaptive controller

where u is the periodic rotor angular position, v is the velocity, u is the control input and a(u) is the unknown position dependent cogging disturbance that repeats in every pole pitch, at the same time a(u) should be bounded and denoting,$|a(\theta)| \leq b_0$The tuning of the controller will bedone in real time from data collected in real time on the system.The way in which information is processed in real time in order to tune the controller for achieving the desired performances will characterize the various adaptation techniques. One clearly sees that an adaptive control system isnonlinear since the parameters of the controller will depend upon measurements ofsystem variables through the adaptation loop. The above problem can be reformulated as nonlinear stochastic control with incomplete information. The unknown parameters are considered as auxiliary states(therefore the linear models become nonlinear: x = ax =⇒ x1 = x1 x2, x2 = v˙˙Where v is a stochastic process driving the parameter variations). Unfortunately,the resulting solutions are extremely complicated and cannot be implemented in practice (except for very simple cases).

Adaptive control techniquescan be viewed as approximation for certain classes of nonlinear stochastic controlproblems associated with the control of processes with unknown and time-varyingparameters.

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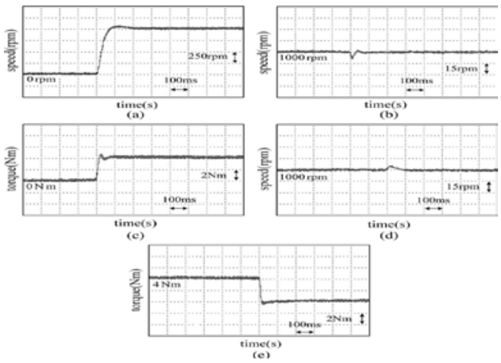

Figure 6 Experiment results under SMC+Adaptive ESMDO controller. (a) Speed. (b) Speed in the case of sudden load increase. (c) Torque in the case of sudden loadincrease. (d) Speed in the case of sudden load decrease. (e) Torque in the caseof sudden load decrease.

D. 4. EXTENDED SLIDING MODEDISTRUBANCE OBSERVER (ESMDO)

The existence of the lumped disturbances will degrade the control performance if the corresponding compensation method is not able to suppress it.

To do this, ESMDO is proposed to estimate the lumped disturbances *r*(*t*) on line. Then, the estimated disturbances are considered as the feed forward part to compensate the disturbances of aforementioned SMC method .According to also because disturbances *r*(*t*) are regarded as the extended system states, an extended dynamic equation can be obtained as

$\dot{\omega} = a_n i_q - cn\omega + r(t) = d(t)$ (8)

Where *d*(*t*) is the variation rate of system disturbances *r*(*t*).Then, the ESMDO can be constructed for system as

$\omega = a_n I_q - c_n \hat{\omega} + \hat{r}(t) + u_{smor}(t) = gu_{smo}$(9)

Where $\hat{\omega}$ is an estimate of speed ω, $\hat{r}(t)$ is an estimate of lumped disturbances *r*(*t*), parameter which is discussed, and u_{smo}represents the switching signal that is designed as

$U\ smo = \eta \cdot sgn(S)$(10)

Whereη is negative. Furthermore, the error equation can be obtained as follows

$\dot{e}1 = -cn\ e1 + e2 + usmo$(11)

$\dot{e}2 = gusmo - d(t)$ (12)

Where$e1 = \hat{\omega} - \omega$ is speed estimation error, and

$e2$ = r(t) −r(t) is disturbance estimation error. Based on the error and the reaching condition of sliding mode the ESMDO parameter choice guidelines are introduced as follows

A.Choice Of Observer Parameter

Parameter η should be selected reasonably to ensure sliding mode occurring, which means that the reaching condition (inequality (2) must be satisfied. Therefore, inequality (2), the reaching condition of sliding mode should be expressed as

$e_1 \cdot \dot{e}_1 = e_1 (-c_n e_1 + e_2 + u_{smo})$(13)

B.Chattering Suppression Analysis

Chattering suppressiontechniques have already become indispensable in SMCsystems.To consider the chattering effect on ESMDO, the first equation of error can be rewritten ase2 = $-u_{smo}$ + Z ,where *Z* represents the chattering signal.F(s) = e2Z − Td(t)=1/Ts + 1

4. SIMULATION by MATLAB

MATLAB is a software package for computation in engineering, science, and applied mathematics. It offers a powerful programming language, excellent graphics, and a wide range of expert knowledge. In MATLAB, that culture contains several elements: an experimental and graphical bias, resulting from the interactive environment and compression of the write-compile-link-execute analyze cycle, an emphasis on syntax that is compact and friendly to the interactive mode, rather than tightly constrained and verbose a kitchen-sink mentality for providing functionality and a high degree of openness and transparency

A.Control Circuit By Simulation View

The Schematic circuit diagram is shown below. Control circuit diagram with sliding mode controller and adaptive extended sliding mode observer.

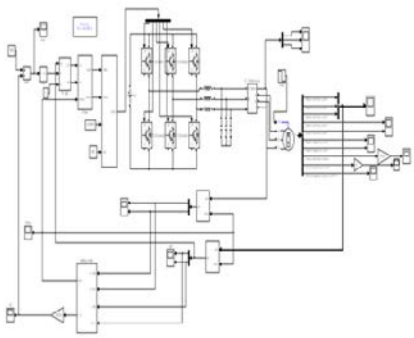

Figure7 The Schematic Control Circuitfor BLDC

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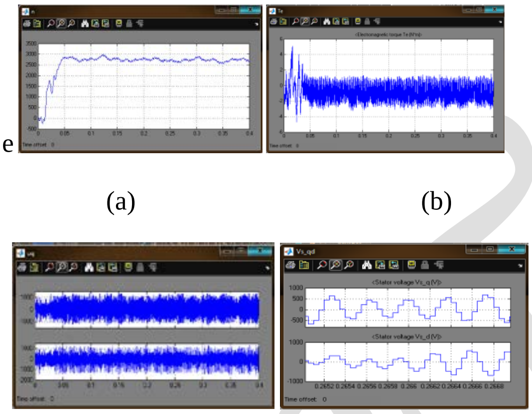
The Sliding Mode segment of the proposed control system, the disturbance observer which observe the disturbance from the parameter of motor and it gives input to the sliding mode controller.This controller, done thetuning process and gives its output to the PI controller. This PI controller get the input and it furthertune and gives its fine output to the space vector PWM and PI controller

B.Simulation Results For Proposed Method

Here output waveform of speed v_s time is shown below ,the waveform refers the less chattering and cogging problem when compared to the PI controller



(a) (b) (c) (d)

Figure 8 CHARACTERISTICS OF BLDC (a)Speed Curve(b)Torque Curve(c)output voltage(d) Quadrature Axis Voltage Disturbance

The total harmonic distortion of both PI controller and SMC+PI+ESMDO are shown below, as per theTHD value proposed SMC+PI+ESMDOis more effective and less chattering and cogging

Table 1 Total Hormonic Distorsion Values

INPUT	PI	SMC+PI+ESMDO
PHASE A	15.8	7.22
PHASE B	10.8	6.19
PHASE C	9.5	2.48

5. EXPERIMENTAL VIEW

A. DSPIC33F

There are two device subfamilies within the DSPIC33F family of devices. They are the General Purpose Family and the Motor Control Family. The General Purpose Family is ideal for a wide variety of 16-bit MCU embedded applications. The variants with codec interfaces are well-suited for speech and audio processing applications.

The Motor Control Family supports a variety of motor control applications, such as brushless DC motors, single and 3-phase induction motors and switched reluctance motor. These products are also well-suited for Uninterrupted Power Supply (UPS), inverters, Switched mode power supplies, power factor correctionand also for controlling the power management module in servers, telecommunication equipment and other industrial equipment.The device names, pin counts, memory sizes and peripheral availability of each family are listed below, followed by their pin diagrams.

B.PIN DIAGRAM

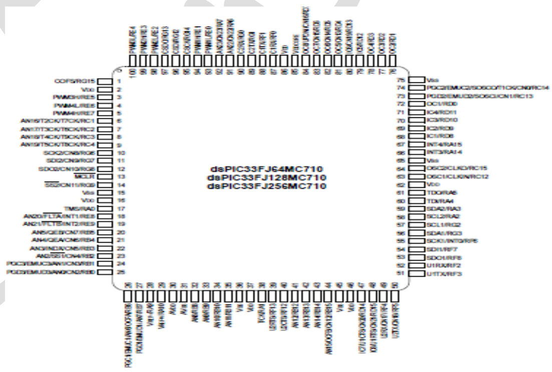


Figure 9 Pin diagram of DSPI33F

6. CONCLUSION

Then one nonlinear SMC algorithm is proposed and has been experimentally applied to a BLDC system, to avoid chattering occurring and to suppress disturbances. The major contributions of this work include,

1) A novel SMRL method is introduced to control chattering
2)In order to estimate system disturbances, one extended sliding-mode disturbance observer is presented
3) A composite control method that combines SMC and ADAPTIVE ESMDO is developed to further improve the disturbance rejection ability of SMC system.

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Here simulation and hardware results are coincide with each other

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