CHAPTER 2 STATE OF THE ART: CONTROL TECHNIQUES

This chapter describes conventional vector control, scalar control approaches for controller design. It also discusses the prevailing controller design approaches and the modifications suggested by researchers for different control applications. It also describes the survey of recent trends in control of motors & drives.

2.1 Introduction

Motor drives are used in wide operating ranges from watts to thousand of kilowatts for different applications of speed and position control systems. Power converter is the key component between power input and motor drives for speed and position control systems. There are three types of motor drives (1) Dc motor drives (2) Induction motor drives (3) synchronous motor drives. AC Induction motor is more commanly used because of its low cost,rugged construction and nearly constant speed operation when operated directly from the supply mains. It is possible to vary the speed of induction motor using power converter. Induction motor drives are classified accoroding to their application as Adjustable speed drives and servo drives.Variable frequency drives employs inverter with controlled or uncontrolled dc to obtain adjustable magnitude of voltage and frequency to supply three phase induction motor drives. Converters used for variable frequency drives are Pulse width modulated voltage source inverter with diode rectifier,square wave voltage source inverter with a thristor rectifer and current source inverter with diode rectifier.PWM inverter controls both magnitude and frequency of output voltage.The total losses due to harmonics are higher then the square wave inverter. In induction motor servo drive application the torque developed by the motor should respond quickly and preciesely to the torque command without oscillations for all speeds. The control of induction motor servo drive is generally implemented using field oriented space vector current control approach [13-16].

The speed and torque of induction motors can be varied by the following techniques,

1. Stator voltage control
2. Rotor voltage control
3. Frequency control
4. Stator voltage and frequency control
5. Stator current control
6. Voltage,current and frequency control

Voltage ,current and frequency control technique is more famous technique for control of speed and torque of induction motor drives systems.

Stator voltage control- Stator voltage can be varied by voltage controllers,voltage fed variable dc link inverters or by Pulse width modulation inverters.AC volage controllers are normally used to provide the volatge control in low power applications with less starting torque and for starting of high power induction motors.

Rotor voltage control- Rotor voltage control can be obtained in wound rotor motor by conneting an external three phase resistance to its slip rings.This method increses starting torque and limits the starting current but it creates unbalances in voltages and currents. The wound rotor induction motors used less compare to squirrel cage induction motors.The three phase resistor may be replaced by a three phase diode rectifier and converter.The dc converter varies the effective resistance

$$R_e = R(1 - k) \tag{2.1}$$

Where k =duty cycle of the converter.

The speed can be conrolled by controlling the effective resistance value and the effective resistance can be controlled by the duty cycle of the converter.

Voltage and Frequency control - To maintain the flux and torque constant it is desired to maintain voltage – frequency ratio constant.This type of control is known as volts/Hertz control.There are three possible arrangements for voltage and frequency control of Induction motor drives.

- Fixed dc and PWM Inverter fed Induction motor drive
- Variable dc and PWM inverter fed Induction motor drive
- Variable dc from dual converter and inverter fed Induction motor driver

Current control – Rotor current or input stator current is controlled for induction motor control.The current is controlled by the current source.Controlled rectifier fed current source or chopper fed current source inverter are used for controlling induction motor drives.To meet the requirements of speed torque characteristics it is also possible to apply voltage, current and frequency control for the different operating regions of induction motor drives.

Frequency control – The induction motor speed can be controlled by controlling the supply frequency.If frequency is reduced and voltage keeping constant the flux increses and causes saturation of the flux and if frequency is increased above its rated value flux and torque reduces.Thus the motor speed can be controlled with constant flux by varying the voltage and the frequency. Classification of different frequency control approches are shown in following fig.

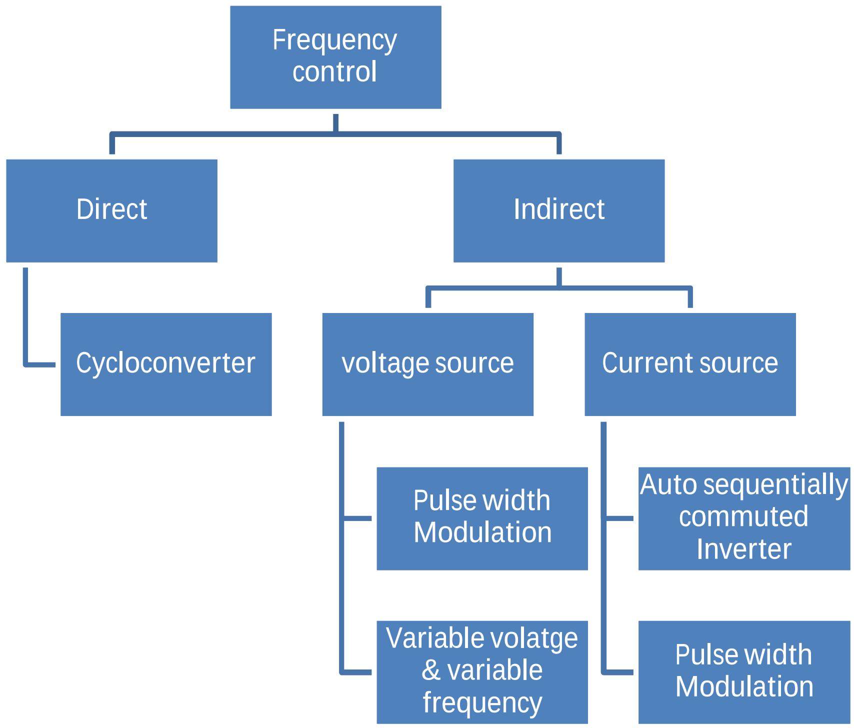

Figure 2. 1 Classification of Frequency control techniques

The close loop control techniques of Induction motor drives are ,

- Scalar control – magnitudes of control variables are controlled
- Vector control – magnitude and phase angles of control variables are controlled
- Adaptive control –controller parameters are continuously varied with the variation of output variables

2.2 Scalar control Techniques

Scalar control approach is based on the magnitude variation of the control parameters. It is voltage controlled technique to control flux, frequency and torque of the machines. The speed of the induction motor is controlled by controlling stator voltage and frequency of the induction motor drive. This technique can be applied for both open and close loop speed control of the induction motor drives [13-16]. Scalar control technique is widely used in industry as it is easy to implement in motor and drives system. Scalar control classified as shown in Fig.2.2

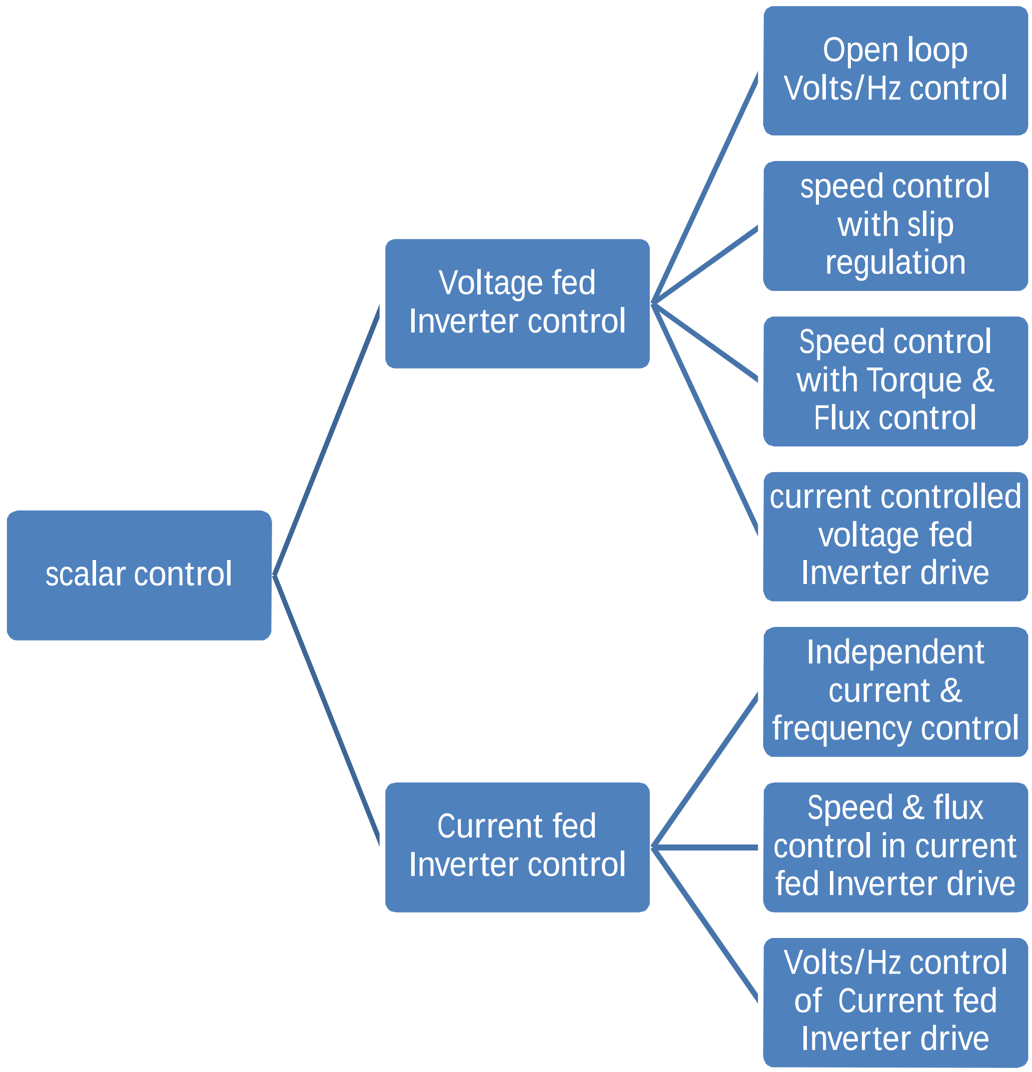

Figure 2. 2 Scalar control using Voltage fed Inverter based induction motor control

Open loop Volts/Hz control –This method of speed control is very popular for induction motor based adjustable speed applications. In adjustable speed applications to maintain the flux constant, voltage is also required to control along with frequency [13-16]. General block diagram of open loop volts/Hz speed control is as shown in Fig.2.3

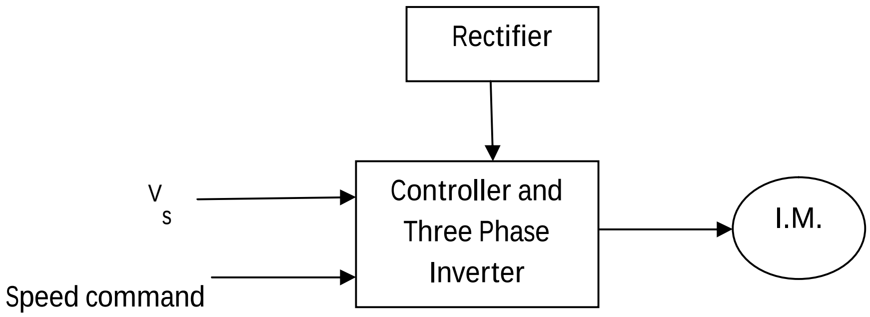

Figure 2. 3 Volts/Hz speed control with voltage fed Inverter

The voltage signal V_s is generated in proportional to variation of frequency to maintain the flux constant. The speed command signal and the voltage signal are used as inputs of the controller to generate controlled pulses. Controlled PWM pulses drive the inverter to control the speed of the induction motor drive system.

Speed control with slip regulation- Close loop of Volts/Hz speed control with the slip regulation gives better speed control performance. General block diagram of close loop speed control with Volts/Hz control and slip regulation is shown in Fig.2.4

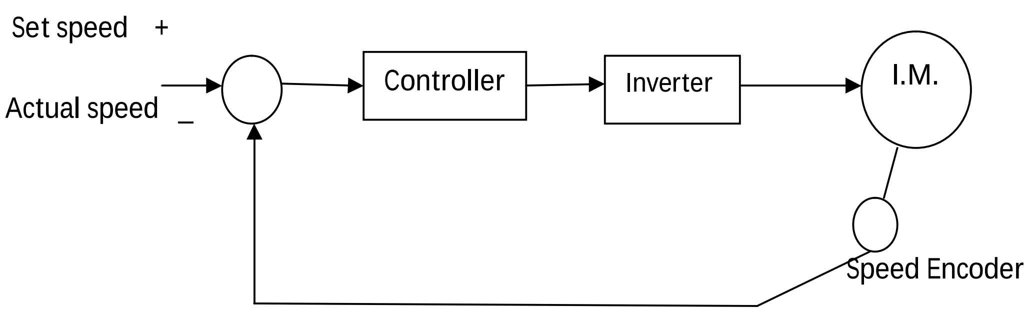

Figure 2. 4 speed control with Volts/Hz control and slip regulation

Actual speed of the induction motor obtained using speed encoder and compared with set speed. The speed error is used as input to the controller. Controller generates controlled PWM pulses based on Volts/Hz speed control approach.PWM pulses drives the inverter fed induction motor drive. If the load torques increases speed decreases. Controller maintains the set speed using frequency signal but with the loss of some flux.

Speed control with Torque & Flux control- Speed controller performance in Volts/Hz approach affected because of flux weakening or flux saturation effect. This results in decrease in torque and acceleration or deceleration of the motor drives. Flux controller along with the speed controller improves the performance of the motor drives. A torque loop within the speed loop also improves the speed response of the system. In scalar control frequency command increased by torque loop and the flux decreases and flux controller maintains the flux.

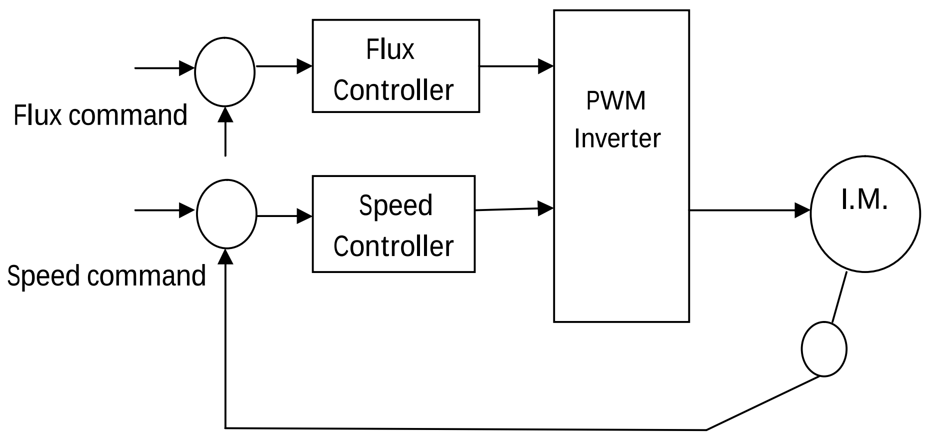

Figure 2. 5 Torque and Flux control system

Current controlled voltage fed Inverter drive –

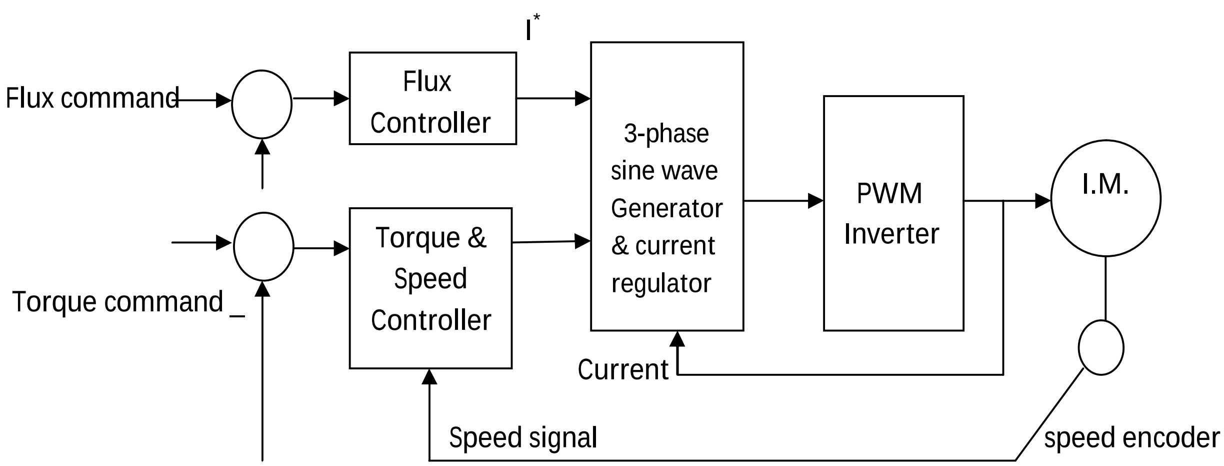

Figure 2. 6 General block diagram of current controlled voltage fed Inverter I.M.drive

This technique uses control of Current instead of stator voltage. Torque control, Flux control and Hysteresis band current control is used to control the speed of induction motor drive system. Flux control system generates stator current magnitude and torque control system generates frequency command for 3-phase sine wave generator. Stator currents signals are sensed by the sensors and feed to current regulator. PWM signals are generated to drive the inverter fed induction motor system. Scalar control technique is easy to implement but due to coupling effect the higher order system may becomes unstable.

2.3 vector control Techniques

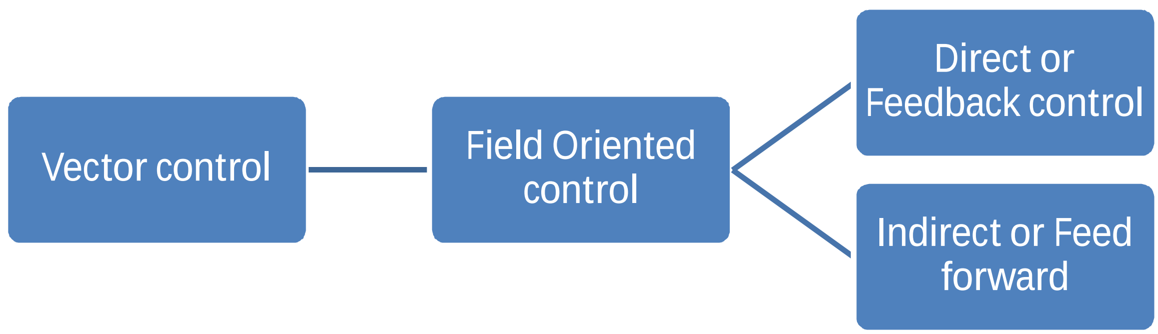

Figure 2. 7 Vector control approach

The vector control or field oriented control invented in 1970s.In this motor drive is controlled like a separately excited dc motor. It is also known as decoupling control, orthogonal control or Trans vector control .This control approach is complex compare to scalar control approach and thus microcontroller or DSPs are needed for the implementation [13-16]. General block diagram of vector control system of induction motor is as shown in Fig.2.8

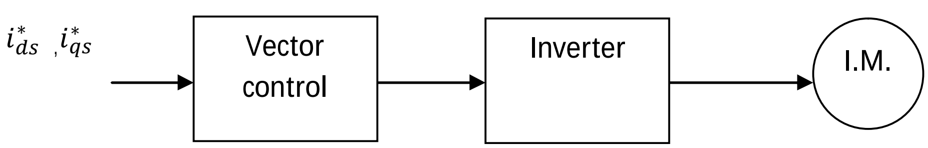

Figure 2. 8 General Block diagram of Vector control of Induction Motor

For vector control of Induction motor consider Induction motor in synchronously rotating reference frame with the variables appeared as dc quantities in steady state, induction motor variables are similar to field current and armature current of the separately excited dc machine.

Direct or Feedback Vector control –

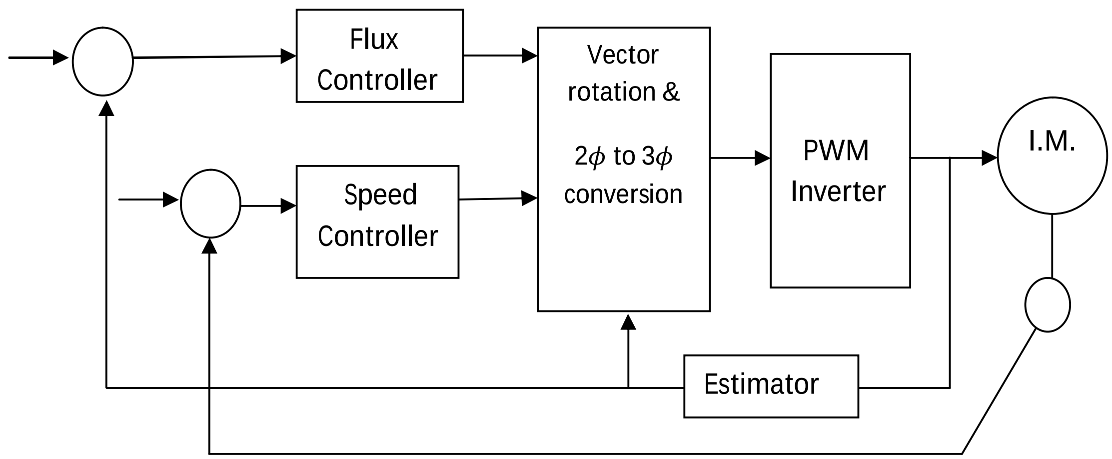

Figure 2. 9 Direct Vector control using Estimator

The vector control parameters i_{ds}^* , i_{qs}^* are converted to stationary frame using flux signals. These stationary frame signals are converted to current signals and fed to inverter fed induction motor drive. The torque component of current is generated using speed control block. The proper alignment of i_{ds}^* in the direction of flux and i_{qs}^* in perpendicular to i_{ds}^* is necessary for the vector control approach. This technique is called direct vector control because of the generation of a unit vector signal directly from feedback flux vectors gives. In this frequency and phase are controlled by unit vector. Speed control is possible in all the four quadrants without the problem of instability.

Indirect or Feed forward vector control – In this technique the unit vector signals are generated using feed forward topology. This approach is commonly used in the applications. The $d^s - q^s$ is fixed and $d^r - q^r$ fixed on rotor but moving at speed ω_r.Synchronously rotating axes $d^e - q^e$ are rotating ahead of $d^r - q^r$ with a slip angle θ_{sl}.Following relations are necessary to implement this technique,

$$\theta_e = \theta_r + \theta_{sl} \tag{2.2}$$

$$\frac{L_r}{R_r}\frac{d\psi_r}{dt} + \psi_r = L_m i_{ds} \tag{2.3}$$

$$\omega_{sl} = \frac{L_m R_r}{\psi_r L_r} i_{qs} \qquad (2.4)$$

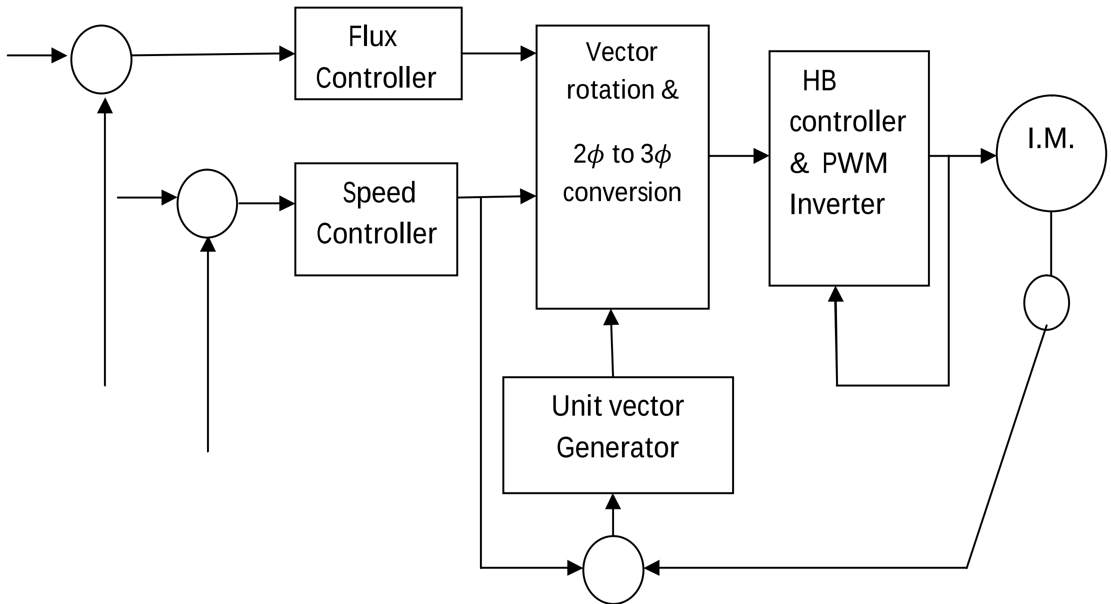

Figure 2. 10 General block diagram of Indirect vector control

The speed control loop generates the torque component of current i_{qs}^* .The flux component of current i_{ds}^* is obtained from the rotor flux. The slip frequency is generated from i_{qs}^* in feed forward manner from the equation 3.Frequency signal ω_e is generated from ω_{sl} & ω_r. Unit vectors are generated from ω_e.Encoder is used to locate the poles with respect to rotor direct axis for the control. In this Hysteresis band PWM current control method is used.

2.4 Recent Trends in control of Motors & drives

In earlier days control of speed and torque of electric motor drives system is done using analog system design. The latest development of microcontroller technology and also in high performance DSPs encourages the design and implementation of digital algorithms using DSPs for motor drives. More complex and advanced control algorithms can be implemented using DSPs. The digital controller gives superior performance than the analog controllers for motor & drives. In [1] Sliding mode controller design method along with svpwm is presented. Performance of Sliding mode controller approach and field oriented control approach for squirrel cage induction motor is compared and simulation and implementation results shows that sliding mode control approach is more efficient with high performance DSP TMS320F2812. In [2] MRAC based vector controlled induction motor drive is presented. The designed algorithm implemented on d-space 1104 based prototype and gives stable operation in the entire four quadrants. In [3] integral sliding mode based flux estimator is used in speed control of induction motor drive. The speed, flux and current controller for vector control approach is designed and comparison of different flux observers is presented. It shows the superior speed tracking performance because of sliding mode control design approach. DTC and Field oriented control or vector controls are the most famous and efficient approaches for the ac drive control. Variable switching frequency restricts or increases the complexity in digital implementation of DTC approach. It also presents digital design and implementation using TMS 2810DSP using Proportional (P) and Proportional Integration (PI) controller [4].Design of Sliding mode observer for rotor speed estimation based sensor less speed control of induction motor shown and implemented using TMS320F2812. Implementation results based on Indirect filed oriented control shows robustness of the designed controller [5].Speed sensor less controller designed using feedback linearization control using discrete time sliding mode observer and implemented using DSP TMS320F2812 platform [7].

Neural network based adaptive estimator designed for sensor less speed control using vector control approach of induction motor drive. The stability problem of the model reference system adaptive system (MRAS) is overcome by the use of artificial neural networks in the controller design [6]. A modification in Indirect Vector Control technique is proposed, which uses extra proportional–integral current controllers with additional motor current feedback signals. Prototype testing is performed on DSP board TC196B for PWM fed CSI based experimental setup [8].Fuzzy logic based sliding mode speed control of induction motor designed and implemented using DSP320F28335. Fuzzy logic is used to reduce chattering effect for the designed sliding mode speed controller based on indirect vector control method. The robustness of the proposed controller is tested for parameter variations [9].Adaptive dynamic sliding mode control system using recurrent RBFN for induction motor drive algorithms designed & implemented using TMS320C31 DSP. Dynamic sliding controller designed using dynamic sliding surface and discrete sliding mode approach reduces chattering compare to conventional sliding mode controller [10]. The open-loop slip compensated scalar scheme presented and gives improved results during both steady state and transient conditions compared with other existing scalar methods. This slip compensated stator flux linkage oriented scheme does not require flux estimation or a speed sensor, only requiring nameplate data, stator current and stator resistance [11]. Self-tuned neuro–fuzzy controller uses fuzzy logic and four layered neural network for speed control of an induction motor drive presented in [12].

Controller is implemented using digital signal processing board DS-1104 on 1/3 hp motor set and gives superior performance compare to conventional NFC and P-I controllers.

SLIDING MODE CONTROL TECHNIQUES

This section gives overview & theoretical back ground of variable structure systems, continuous time sliding mode control, equivalent control & reaching law approach, discrete time sliding mode control and concept of multi rate output feedback based discrete time sliding mode control technique for controller design. This chapter also presents design and development of Multi rate output feedback (MROF) and multi segment sliding mode control (MSMC) based controller design.

2.5 Sliding Mode Control

Control problems related to plant parameter uncertainties, disturbances and high-order dynamics remain as big challenges for control engineers. Non linear control techniques are most demanding for the development of robust control systems to achieve relevant control objectives. As a result, considerable progresses have been attained in robust control techniques, such as nonlinear adaptive control, model predictive control, back stepping, sliding model control etc. Sliding Mode Control is a systematic approach to controller design while allowing stability in the presence of parametric uncertainties and external disturbances

Variable structure control systems (VSC) evolved in early 1960s in Russia and becomes popular through a book by Itkis in 1976 and also by survey paper of Utkin in 1977.Variable structure control systems are a class of systems whereby the control law is deliberately changed during the control process according to some defined rules which depends on the state of the system [47]. Variable structure systems may be used for controller design of varying structure in which dynamics of the systems not realized by single control structure. Sliding mode control is a type of variable structure control (VSC). Sliding Mode control Techniques are most popular in the fields of electrical, mechanical, aerospace and chemical engineering applications such as automated control of drives, navigation systems and surface transport systems. The increasing use of intelligent control systems explores more challenges for robust sliding mode control techniques. Sliding Mode control is in the class of nonlinear control systems and it also introduces discontinuities into the control systems.

Sliding mode is defined as “Motion of the system trajectory along a ‘chosen’ line/plane/surface of the state space” This chosen line/plane/surface of the state space is called the sliding or hyper surface. The sliding surface is described by $s = 0$, and the sliding mode along the surface commences after the finite time when system trajectories have reached the surface [49]. In the sliding mode control system, the control must be designed such that it drives the trajectories to the switching surface and maintains it on this surface once it has been reached. The attractivity of the sliding surface or reachability condition is expressed as [46, 49],

$$s\dot{s} < 0 \tag{2.5}$$

Sliding Mode Control is the control system designed to achieve sliding mode. The Sliding Mode Control approach consists of two steps: (1) The first step is the selection of a manifold/surface in the state space by considering system specifications and constraints to obtain desired performance of the control systems. (2) The second step is design of control law such that system states reaches on selected sliding surface/sliding manifold in finite time. Control law ensures the desired performance of the controller even in the presence of disturbance and uncertainties.

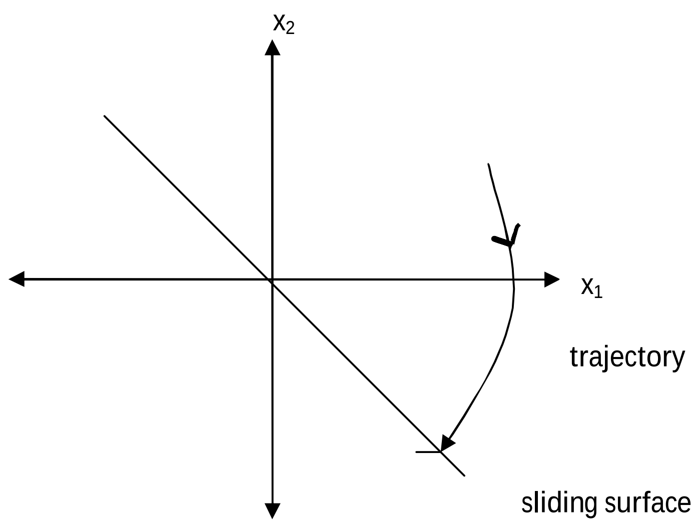

Figure 2. 11 Phase portrait of a sliding motion [46-50]

In Sliding mode control system ideal sliding mode exists only when the state trajectory x (t) of the controlled plant attends the desired trajectory at every time instant, which requires fast switching. In real systems, a switched controller has imperfections, which limit switching to a finite frequency and it oscillates within a neighborhood of the switching surface. This is because of discontinuous nature of control laws of sliding mode control system. The discontinuity in the feedback control produces a particular dynamic behavior in the vicinity of the surface, which is called "Chattering".

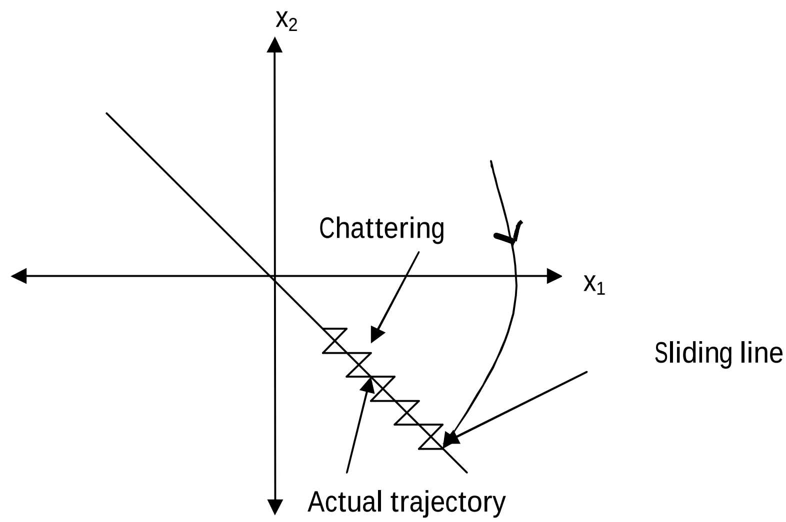

Figure 2. 12 chattering phenomena [46-50]

Chattering may excite unmodeled high frequency modes, which degrades the system performance. It also leads high wear of mechanical parts or actuators and also produces heat losses in electrical power circuits. This may be eliminated using regulation scheme with the switching surface. chattering may be attenuated using high gain feedback approach, boundary layer or sliding sector approach, inserting integrator in the system, sliding mode controller design with artificial intelligent techniques such as fuzzy logic, neural network etc.

The effectiveness of variable structure control system shown by following example [45-49].

Consider the system

$$\ddot{x} = -\psi x \tag{2.6}$$

$$Where\ \psi = \propto_1^2\ and\ \psi = \propto_2^2\ with\ \propto_1^2 > \propto_2^2$$

The resultant dynamic in both cases would be ellipse in the phase as given in figs. System is not asymptotically stable. The switching logic used for the system is given by

$$\psi = \begin{cases} \propto_1^2\ if\ x\dot{x} > 0 \\ \propto_2^2\ if\ x\dot{x} \leq 0 \end{cases} \tag{2.7}$$

The result of the switching logic is shown in fig.

The effectiveness of Sliding mode based variable structure systems [46] shown in following example,

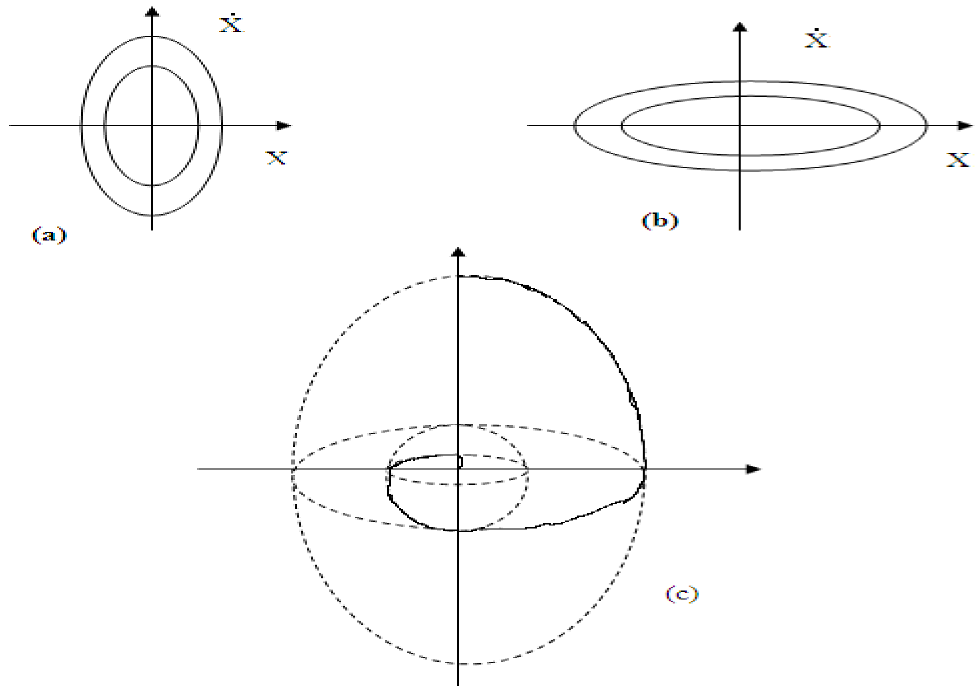

Figure 2. 13 Phase planes (a), (b), phase plane of composite system with VSS (c) [46-47]

Consider the second order systems,

$\ddot{x} - ax = u, a > 0$ (2.8)

$u = -k|x|sign\,(s)$ (2.9)

$s = cx + \dot{x}, k > 0, c > 0$ (2.10)

Unstable structure systems are shown in fig (a) & (b). Using VSS approach System structure varies along the switching lines s=0 and x=0 and also enforcing the sliding mode and system becomes asymptotically stable as shown in fig.(c).The switching line is reached for any initial conditions. In control processes the output may be vector valued quantity and all the output states are not measurable leads to concept of multidimensional sliding modes. Sliding motion may appear in an intersection of several surfaces if the control is a vector valued and each component with discontinuities in its own switching surface [46], for example system described by non linear differential equations in an arbitrary n-dimensional state space with m-dimensional vector control

$$\dot{x} = f(x, t, u) \tag{2.11}$$

With $x \in R^n, f \in R^n, u \in R^m$ and t denoting the time. The control is selected a discontinuous function of the state.

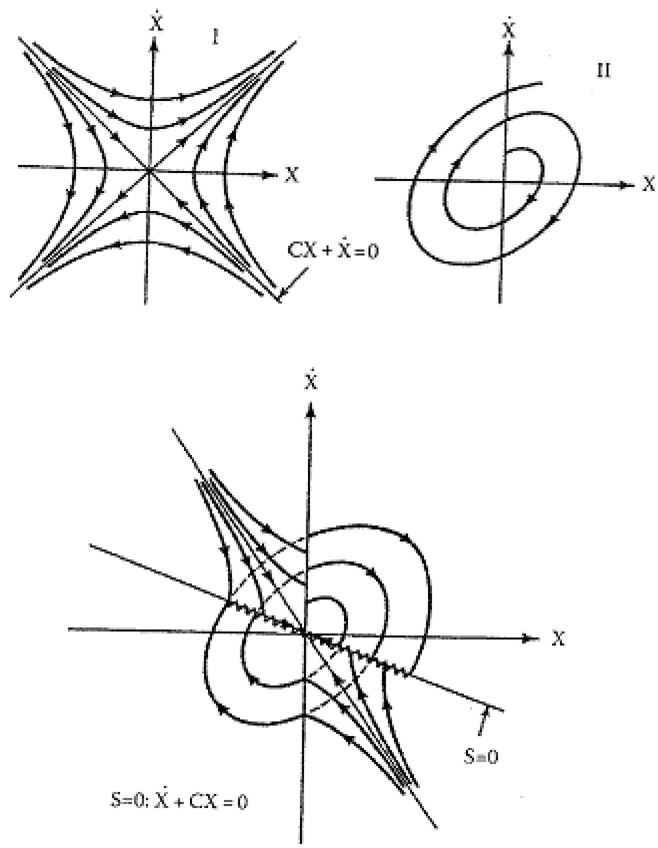

Figure 2. 14 variable structure systems (a), (b), state plane of variable structure system (c) [46-50]

Each component of the control u_i may undergo discontinuities on some nonlinear surface $s_i(x) = 0$ in the state space.

$$u_i = \begin{cases} u_i^{+}(\text{x, t}) \text{ if } s_i(x) > 0 \\ u_i^{-}(\text{x, t}) \text{ if } s_i(x) < 0 \end{cases} \quad i = 1,2, \ldots, m$$

Where $u_i^+(x,t)$ and $u_i^-(x,t)$ are continuous state functions. For above system sliding mode may occur in the intersection of m surfaces $s_i(x) = 0, (i = 1,2, \dots, m)$ .For high dimensional plants, sliding mode is designed using decoupling of the overall system motions into independent partial components results in simplification of the design procedure. The decoupling and invariance properties make sliding mode methodology an efficient tool to control complex electrical and mechanical systems. Induction motor with unknown load torque and inertia with position, speed or torque may be controlled by this approach. Implementation aspects of sliding mode control uses power electronic converters. Sliding mode control in Non linear systems [48] For example,

$$\dot{x} = f(x) + g(x)u(t) \tag{2.12}$$

switching surfaces,

$$S = \{x \in R^n : s(x) = [\, s_1(x), \dots, s_m(x)]^T = 0\} \tag{2.13}$$

Equivalent control obtained by $\dot{s}(x)$=0 given as,

$$u_e = -\left[\frac{\partial s}{\partial x} g(x)\right]^{-1} \frac{\partial s}{\partial x} f(x) \tag{2.14}$$

Therefore resulting dynamics with sliding mode is given by,

$$\dot{x_e} = \left[I - g(x_e)\left[\frac{\partial s}{\partial x_e} g(x_e)\right]^{-1} \frac{\partial s}{\partial x_e}\right] f(x_e) \tag{2.15}$$

For particular cases sliding surface must be designed such that $\frac{\partial s}{\partial x} g(x)$is regular .To reduce the complexity in determination of switching surface , system can be transformed into regular form and then control law may defined so that sliding mode occurs on $s = 0$.

2.6 Equivalent control & Reaching law approach

The solution concept proposed by Filippov for differential equation with discontinuous right hand sides constructs the average solutions approaching from the point of discontinuities. Then more recent approach of differential inclusions is taken by Ryan. The equivalent control is the control action necessary to maintain an ideal sliding motion on S. The method of equivalent control is proposed by Utkin in 1977. Consider the system [45] described by the equation,

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (2.16)$$

Hyper plane,

$$S = \{x \epsilon R^n : s(x) = 0\} \quad (2.17)$$

Suppose at t_s system states lie on S and sliding mode takes place. If we multiply above equation (2.16) by S then,

$$S\dot{x}(t) = SAx(t) + SBu(t) = 0 \; for\; all\; t \geq t_s \quad (2.18)$$

Then equivalent control for the system is,

$$u_{eq} = -(SB)^{-1}SAx(t) \quad (2.19)$$

Therefore ideal sliding motion is given by,

$$\dot{x}(t) = (I_n - B(SB)^{-1}S)Ax(t) \;\; for\; all\; t \geq t_s \;\; and\; Sx(t_s) = 0 \quad (2.20)$$

The trajectories of s(t) must be directed towards the sliding surface [45].

$$\lim_{S \to 0^+} \dot{s} < 0 \; and \; \lim_{S \to 0^-} \dot{s} > 0 \quad (2.21)$$

In domain $\Omega \subset R^n$,sliding surface , $D = S \cap \Omega = \{x \in \Omega : s(x) = 0\}$

The above equation (2.21) is also given by,

$$s\dot{s} < 0 \quad (2.22)$$

The equations in (2.21) & (2.22) are known as reachability condition. If the reachability condition is satisfied for $\Omega = R^n$ then

$$\frac{1}{2}\frac{d}{dt}s^2 = s\dot{s}$$

It follows the function $V(s) = \frac{1}{2}s^2$ is a Lyapunov function for the state s.

Stronger condition guaranteeing an ideal sliding motion is the η-reachability condition given by

$$s\dot{s} \leq -\eta\,|s| \quad (2.23)$$

Where η is small positive constant. Integrating above equation from 0 to t_s,

$$|s(t_s)| - |s(0)| \leq -\eta t_s \quad (2.24)$$

$$t_s \leq \frac{|s(0)|}{\eta} \tag{2.25}$$

The above equation gives time taken to reach s=0.

2.7 Multi Rate output feedback (MROF) Approach

Classical controller design techniques such as Nyquist, Bode plots are normally used for linear control system design with fixed plant parameters. For Non linear control system with plant parameter variation, adaptive control system design techniques are more effective. Adaptive control Techniques can be classified as self tuning control ,MRAS ,Sliding mode or variable structure control, Expert System control, Fuzzy Control ,Neural Control.[14].A sliding mode control (SMC) with a variable control structure is basically an adaptive control that gives robust performance of a drive with parameter variation and load torque disturbance.SMC is non linear and can be applied to a linear or non linear plant . The variable structure system with sliding modes is the recent research domain in control of electric drives, robotics and position control applications.SMC is used for power converter control and also for drive regulation [15,18,23]

In controller design the state feedback controller can be obtained by pole placement approach and linear quadratic regulator (LQG) approach. In pole placement approach desired system poles are selected using feedback gain matrix. Feedback gain matrix requires measurement of all state variables or state estimator (observer) is needed to estimate the state variables. State Feedback gain matrix can be determined by transformation matrix, direct substitution method, Ackermann's method. All the state variables are measurable then it is easy to design state feedback controller. In practical condition it is not possible to measure all the actual states variables and therefore state feedback controller do not perform well with parameter variation and uncertainty. Observer based state feedback controller also not gives desired performance. One of the solutions to design the controller for the system with insufficient state information is to apply output feedback approach. Multi rate output feedback can be realized using Fast Output Sampling (FOS) or by Periodic Output Feedback (POF). In fast output sampling technique system output is sampled faster than the control input. Multi rate output feedback approach using fast output sampling gives superior performance. Fast output sampling technique also assures close loop system stability [44].Multivariable systems with higher order more effectively designed by state space approach of sliding mode controller design.

2.8 Multi rate output feedback for d.c.motor control (MROF)

Drives are used in Electro mechanical plant in modern Industrial applications. Direct current motors are very commonly used as variable speed drives and in applications where severe torque variations occur. In the applications like actuators for motion control ,robot arms, conveyor belts, dc switching converters , Process control systems, electrolytic process, welding processes, D.C.motor is the key component. Small d.c.machines are used primarily as control devices such as techo-generators for speed sensing and servomotors for positioning and tracking. Separately excited D.C.motors are used in applications like paper machines, diesel-electric propulsion of ships and in steel rolling mills.

D.C. motor Controller can be designed using the control variable as speed, position, torque, armature current .Conventional Proportional Integral type controller are sensitive to parameter variations, load variations, system uncertainty, external disturbance[19]. Sliding mode control technique is more popular in variable speed drive because of its insensitivity to parameter variations and load variations and external disturbance. Sliding mode controller can be designed for different purpose such as current control, speed control, torque control and position control. Integral SMC is designed in [17] for D.C.Motor Position control system. Chattering is the main drawback and it is reduced by incorporating switched gains in the design of Integral SMC or by appropriate design of control law. In [22] sliding surface is designed using intelligent approach like fuzzy logic to reduce chattering. Finite speed of switching devices involved in SMC cause the phenomenon of chattering and it affects the performance of the system. It causes high frequency oscillations in the output, heating up of electrical circuits and wear in actuators. This controller offers good tracking performance and robustness property [17,20,21]. Continuous time SMC is designed in [21] for D.C.Motor position control system using equivalent control approach for lightweight single-link flexible arm with high varying payload.

Discrete time sliding mode was introduce for implementing SMC in real time sampled data systems.[24,40-43].With the latest development in Digital Signal Processing Technology and increasing use of computers in control applications ,discrete sliding mode control systems are more popular. In the case of discrete time sliding mode control, the measurement and control signal application are performed only at after regular intervals of time and the control signal is held constants in between these instants.

Multi rate Output Feedback (MROF) is the concept of sampling the control input and sensor output of a system at different rates. It provides time delay required for control law implementation. It has advantages of both state feedback and output feedback control approaches [25,26,27,35].

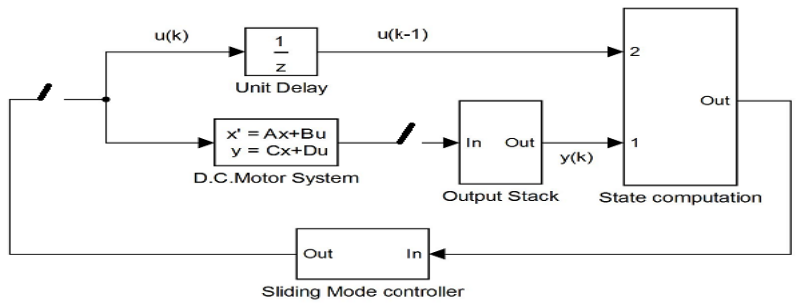

Figure 2. 15 Multi rate output Feedback(MROF) based DSMC for D.C.motor system [25]

Sliding mode controller is designed using state space approach. Discrete-time Sliding Mode Control Algorithm based on Multi rate Output Feedback approach for D.C.Motor Position Control is presented. System model for MROF based controller as shown in Fig-2.15.

Consider the discrete system,

$$x\big((k+1)\tau\big) = \phi_\tau x(k\tau) + \Gamma u(k\tau)$$
$$y(k\tau) = Cx(k\tau) \qquad (2.26)$$

For the discrete time system having t = $k\tau$,the previous output samples for discrete system as

$$y_k = \begin{bmatrix} y(k\tau-\tau) \\ y(k\tau-\tau+\eta) \\ \vdots \\ y(k\tau-\eta) \end{bmatrix} \qquad (2.27)$$

Multi rate output sampled system can be represented by,

$$x(k+1) = \phi x(k) + \Gamma u(k)$$

$$y_{k+1} = C_0 x(k) + D_0 u(k) \tag{2.28}$$

Where

$$C_0 = \begin{bmatrix} C \\ C\phi \\ \vdots \\ C\phi^{N-1} \end{bmatrix} \qquad D_0 = \begin{bmatrix} 0 \\ C\Gamma \\ \vdots \\ C\sum_{j=0}^{N-2} \phi^j \Gamma \end{bmatrix} \tag{2.29}$$

2.8.1 System Model

This section represents mathematical model of separately excited dc motor and its state space representation in continuous time and discrete time domain. The parameters defined for above state space model as L_a= Inductance of armature winding (H), R_a= Resistance of armature winding (ohm), e_b = back emf (volts), T_M= torque developed by the motor (N-m), J= equivalent moment of inertia of motor (kg-m^2), u = applied armature voltage. B= equivalent viscous friction coefficient of motor (N-m/ (rad/sec)) K_T = motor torque constant (N-m/amp), K_b= back emf constant (volts/ (rad/sec)).

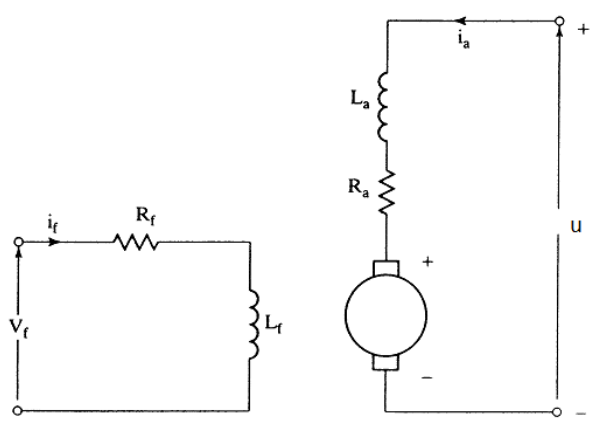

Figure 2. 16 Separately excited d.c.motor [2]

2.8.2 State-Space Representation of the system

Separately excited dc motor with armature voltage control shown in Fig-2.16[15], the State space model for d.c.motor position control [33,38] obtained as follows for State variables $x_1(t) = \theta(t)$, $x_2(t) = \omega(t)$, $x_3(t) = i_a(t)$, and $y(t) = \theta(t)$.

Continues time State space model is obtained as,

$$\dot{x}(t) = Ax(t) + bu(t)$$
$$y(t) = cx(t) \quad (2.30)$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{B}{J} & \frac{K_T}{J} \\ 0 & -\frac{K_b}{L_a} & -\frac{R_a}{L_a} \end{bmatrix}; \quad b = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix} \quad (2.31)$$

$$c = [1 \quad 0 \quad 0] \quad (2.32)$$

Discrete state space model of d.c.motor is obtained by discretizing the above system sampled at a sampling interval τ sec be represented as

$$x\big((k+1)\tau\big) = \phi_\tau x(k\tau) + \Gamma u(k\tau)$$
$$y(k\tau) = Cx(k\tau) \quad (2.33)$$

Where

$$\phi_\tau = e^{A\tau}, \quad \Gamma = \int_0^\tau e^{A\tau} bd\,\lambda \quad (2.34)$$

2.8.3 MROF based DSM controller design

To design the controller it is necessary to measure input and output states of the system. In practice it is not always possible to measure all the input and output states of the system. Multirate output feed back (MROF) sampled system does not need the system state for feedback and uses output samples for the controller design[29,30] .In this control input and output is sampled at different sampling rate. Discrete controllers are more popular due to rapid developments in digital computer technology. Discrete time sliding mode control has been applied here for separately excited d.c.motor position control using multi rate output feed back (MROF). Sliding Mode controller design consist of two stages hyper plane or switching surface design and control law design. [17, 25, 26, 40]. Following Reaching Law applied here for the design

$$s(k+1) - s(k) = -q\tau s(k) - \epsilon\tau sgn\big(s(k)\big), \quad \epsilon > 0,\ q > 0,\ 1 - q\tau > 0 \tag{2.35}$$

The switching surface defined as follows

$$s(k) = c^T x(k) = 0 \tag{2.36}$$

Multirate output[27,31] to state relationship,the state $x(k)$ can be expressed in terms of system outputs y_{k+1} and control input $u(k)$ as

$$x(k) = \left({C_0}^T C_0\right)^{-1} {C_0}^T \left(y_{k+1} - D_0 u(k)\right) \tag{2.37}$$

By substituting the value of $x(k)$, $x(k+1)$ can be obtained as

$$x(k+1) = L_y y_{k+1} + L_u u(k) \tag{2.38}$$

Where

$$L_y = \phi_\tau \left({C_0}^T C_0\right)^{-1} {C_0}^T$$

$$L_u = \Gamma_\tau - \phi_\tau \left({C_0}^T C_0\right)^{-1} {C_0}^T D_0 \tag{2.39}$$

Using the above relations control input function for MROF obtained as ,

$$u(k) = Fx(k) + \gamma sgn\big(s(k)\big) \quad (2.40)$$

$$where\ F = -(c^T\Gamma_\tau)^{-1}[c^T\phi_\tau - c^T I + q\tau c^T]$$
$$\gamma = -(c^T\Gamma_\tau)^{-1}\epsilon\tau$$

2.8.4 Simulation Results

Simulations are obtained for d.c.motor position control using Multi rate output Feedback (MROF)[35-37,40].Discrete system modelling with MROF obtained and represented by the equations (2.28-2.29) and for Sliding mode approach, Sliding surface was given by equation (2.36),reaching law was given by equation (2.35) and control input obtained as shown in equation (2.40) used for the simulations study.

The parameters of separately excited d.c.motor are same as used in [28] as R=7.5ohm, J=0.006kgm^2, L=5mH B=0.005Nms, K_b=K_T=0.809. The parameters for the discrete sliding mode control were τ = 0.3; q=1; ϵ =0.05;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -0.694 & 112.36 \\ 0 & -161.8 & -1500 \end{bmatrix};\quad b = \begin{bmatrix} 0 \\ 0 \\ 200 \end{bmatrix} \quad (2.41)$$

$$C = [1 \quad 0 \quad 0] \quad (2.42)$$

This system is sampled at τ = 0.3

$$\phi_\tau = \begin{bmatrix} 1 & 0.0764 & 0.0057 \\ 0 & 0.0209 & 0.0016 \\ 0 & -0.0023 & -0.0002 \end{bmatrix};\quad \Gamma_\tau = \begin{bmatrix} 0.2614 \\ 1.1447 \\ 0.0099 \end{bmatrix} \quad (2.43)$$

$$C_\tau = [1 \quad 0 \quad 0] \quad (2.44)$$

The system is also sampled at del=0.1 given by,

$$\phi_{del} = \begin{bmatrix} 1 & 0.0566 & 0.0042 \\ 0 & 0.2770 & 0.0209 \\ 0 & -0.0301 & -0.0023 \end{bmatrix} ; \quad \Gamma_{del} = \begin{bmatrix} 0.0507 \\ 0.8451 \\ 0.0425 \end{bmatrix} \tag{2.45}$$

$$C_{del} = [1 \quad 0 \quad 0] \tag{2.46}$$

The sliding surface coefficient c obtained [25-27, 30, 35, 36] is given by,

$$c = \begin{bmatrix} 2.4 \\ 2.0226 \\ 1.734 \end{bmatrix} \tag{2.47}$$

$$L_0 = \begin{bmatrix} 0 & -0.2747 & 1.2747 \\ 0 & -1.3446 & 1.3446 \\ 0 & 0.1463 & -0.1463 \end{bmatrix} ; \quad L_1 = \begin{bmatrix} 0.0848 \\ 1.0119 \\ 0.0243 \end{bmatrix} \tag{2.48}$$

Control input from equation given by,

$$F = [-0.2433 \quad 0.4034 \quad 0.4046] \tag{2.49}$$

$$\gamma = [-0.0051] \tag{2.50}$$

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(Online:http://www.ijecee.com/uploads/displayVolumeIssue/V-4-I-4-ID-2.pdf)

Sliding surface for the MROF based speed control system is shown in above Fig.2.18.Sliding surface is stabilize to 0 value in some samples. The control parameters position, velocity and armature current reaches to desired value as shown in Fig.2.19, 2.20 and 2.21 respectively.

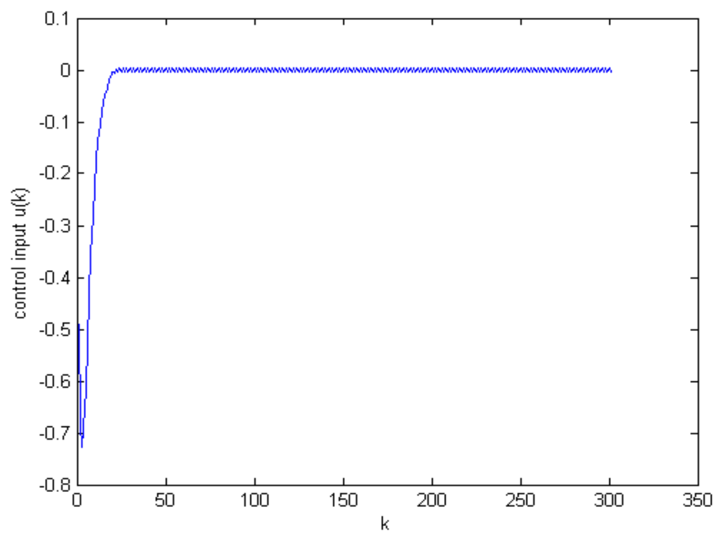

Figure 2. 17 ***Control Input u***

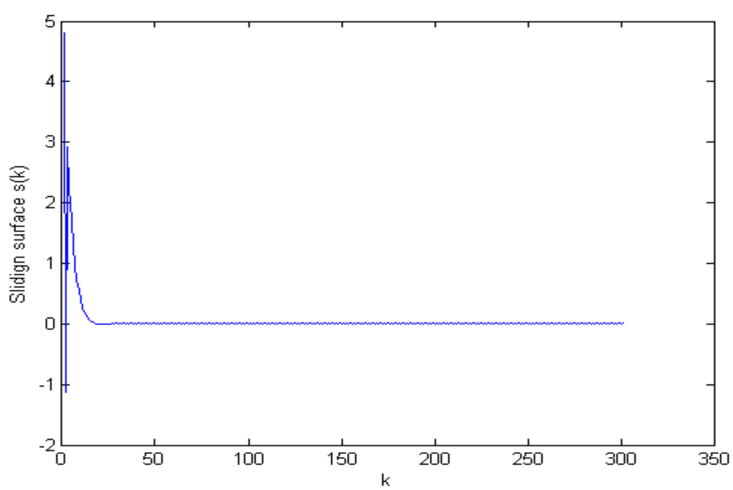

Figure 2. 18 ***Sliding Surface S***

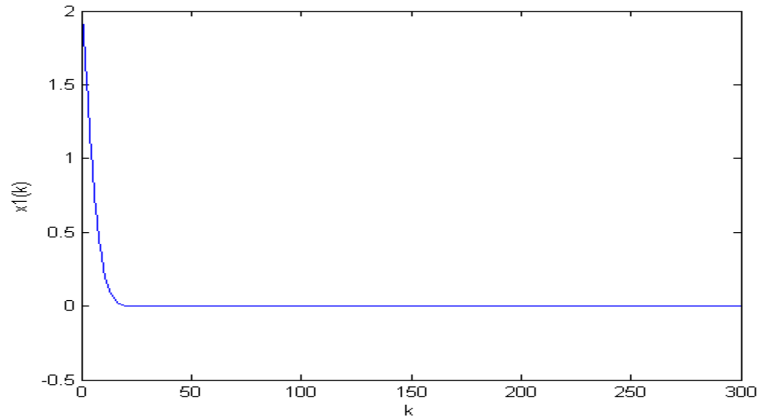

Figure 2. 19 ***Position state x_1***

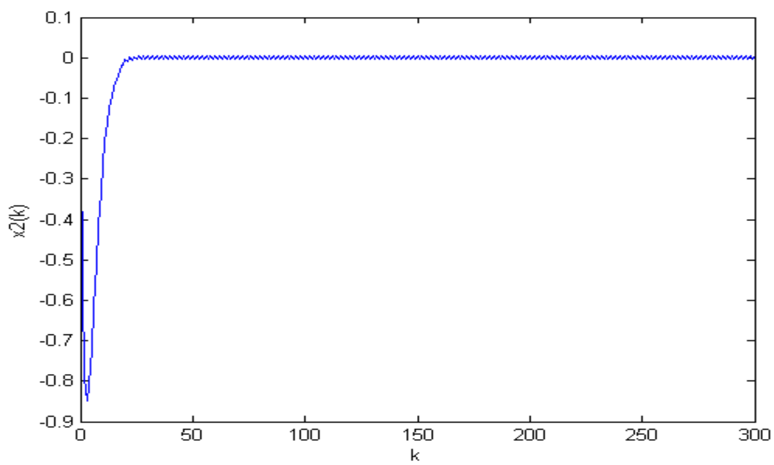

Figure 2. 20 Angular velocity state x_2

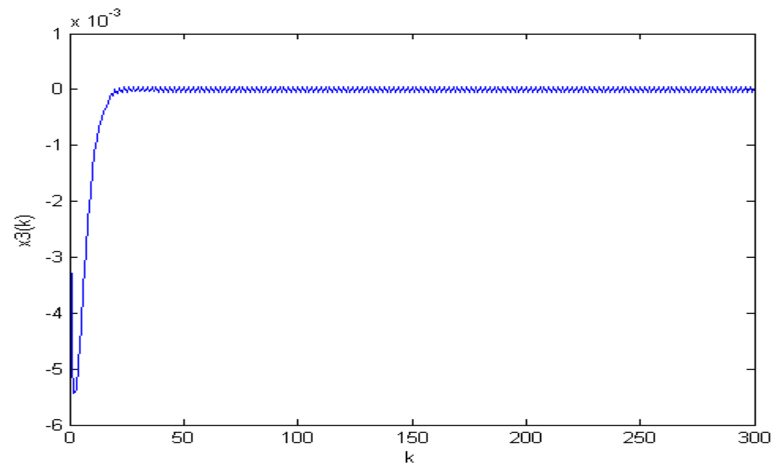

Figure 2. 21 Armature current state x_3

2.9 Summary

This chapter explains the conventional control approaches for Induction motors & drives. It also discusses different scalar and vector control techniques along with the conceptual control block diagram for motors and drives. It also reviews the use of high performance controllers and soft controller techniques with the conventional control techniques to improve the performance of the system for the motors and drives. Conventional sliding mode controller design concepts along with Equivalent and reaching law approach is explained. Continuous time mathematical model has been used for obtaining discrete state space model. Design of discrete sliding mode control using Multirate output feedback approach is presented. Design and Implementation of DC motor controller is also presented in detail. Simulation results shows that Discrete sliding mode controller using Multirate output feedback (MROF) approach brings position control system error states of d.c.motor to zero from the initial conditions.