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A THEORETICAL APPROACH OF NON-LINEAR ANALYSIS FOR AN ELECTRIC DRIVE SYSTEM USING STATE SPACE TECHNIQUE

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Abstract -- ***Electrical motors are key to the growth of any modern society. Electrical drives plays dominant source of mechanical power in different applications such as process industries, production and etc. Feedback control techniques are used to improve the performance of the drive system in terms of achieving desired motion control, fast response & etc. The development of control algorithms used to compensate non-linearity such as friction, backlash & transmission compliance. And the overall control performance efficiency, availability and reliability have been improved, thus accelerating their penetration into various engineering applications***.

Key words: ***Electric drive system, Modeling, State space analysis, Non linearity, Model Predictive Control.***

1. INTRODUCTION

In spite of linear dynamical systems, observability analysis is a very difficult task for nonlinear dynamical systems. Furthermore, observable systems, linear or nonlinear, do not show same behaviors with different observers. Global observability analysis of permanent magnet synchronous motors (PMSM)

This paper describes an overview of controlling electric drives in various fields. To perform this, control system will be designed. The general analysis includes mathematical model, electronic power converter, sensor, electronic control units and basic control strategies.

In order to ensure optimal utilization of the motors, the shaft speed and armature current must be controlled. Currently, the most efficient way of achieving both speed and current control in electrical motors is through power electronic switching, thus making the system both nonlinear and time varying. The combination of electric motors and control electronics is referred to as electric drives. Due to the inherent nonlinear nature of electrical drives, the system is prone to complex dynamical phenomena including bifurcations, chaos, coexisting attractors and fractal basin boundaries.

The figure shows below is controlled electric drives.

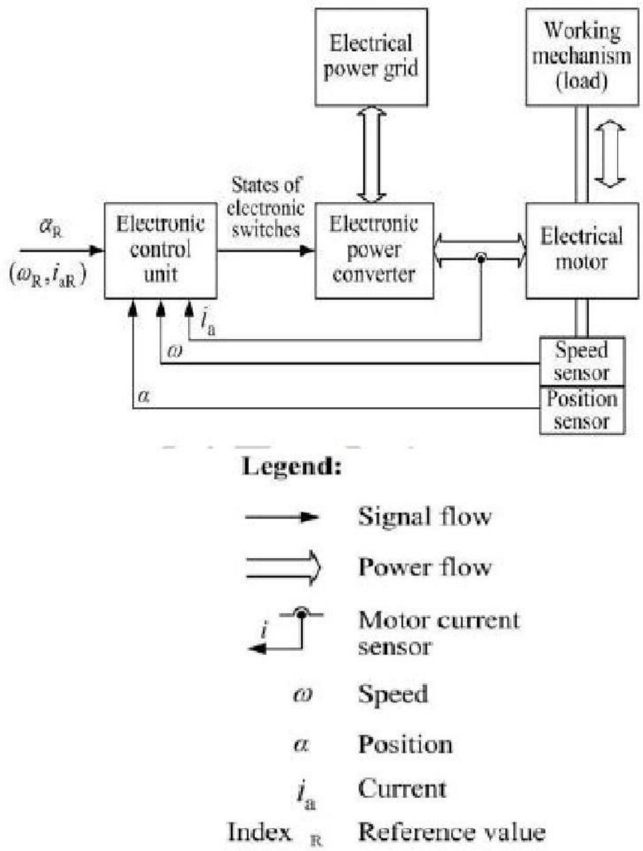

Fig.1: Block diagram of a Drive System

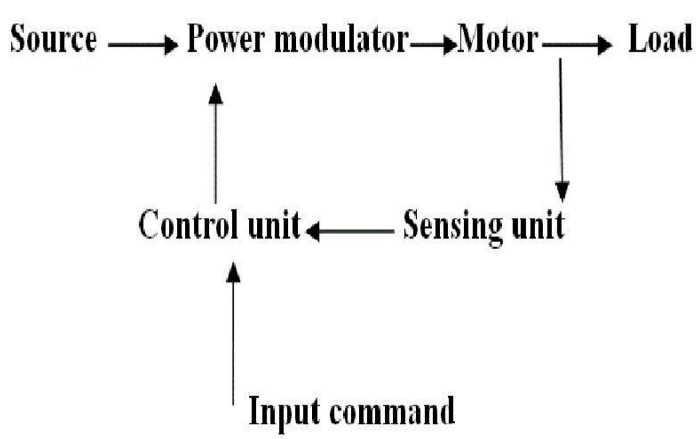

Fig. 2: Representation of an Electric Drive

Whenever the term electric motor or electrical generator is used, we tend to think that the speed of rotation of these machines is totally controlled only by the applied voltage and frequency of the source current. But the speed of rotation of an electrical machine can be controlled precisely also by implementing the concept of drive. The main advantage of this concept is, the motion control is easily optimized with the help of drive. In very simple words, the systems which control the motion of the electrical machines are known as electrical drives. A typical drive system is assembled with a electric motor and a sophisticated control system that controls the rotation of the motor shaft. Now days, this control can be done easily with the help of software. So, the controlling becomes more and more accurate and this concept of drive also provides the ease of use. This drive system is widely used in large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc. Drives are employed as prime movers for diesel or petrol engines, gas or steam turbines, hydraulic motors and electric motors.

Now coming to the history of electrical drives, this was first designed in Russia in the year 1838 by B.S.Iakobi, when he tested a DC electric motor supplied from a storage battery and propelled a boat. Even though the industrial adaptation occurred after many years as around 1870. Today almost everywhere the application of electric drives is seen.

Advantages

Simplicity
Ease and smooth control
Flexible
Compactness
Reliability Long life
Cleanliness Easy
starting
High power factor operation Low
cost
Facility for remote control
Available in wide range of torque and speed
Energy saving than direct source

Besides having so many advantages, it has some disadvantages too which are

Disadvantages

Non availability on failure of supply
Cannot be employed in distant places
Causes noise pollution

2. OVERVIEW OF NONLINEAR DYNAMICAL SYSTEMS

Dynamics can be defined as a science of change and dynamical systems are replete in nature. This includes the motion of the planets, the motion of fluids, the flow of current in electric circuit, the dissipation of heat in solids, the propagation and detection of seismic waves, and the increase and decrease of human or animal population.

Virtually all dynamic systems are composed of:

- ✓ A set of independent *state variables* which evolve with time and can be used to completely describe the behavior of the system.

- ✓ A function which connects the rate of change of the state variables with the state variables themselves and other system inputs and parameters.

The time evolution of these state variables can be modeled by using either a *differential equation* or a *difference equation*, and such models are developed by applying some physical laws such as Newton's laws of motion, Kirchhoff's laws, Faradays laws etc.

The block diagram of a typical dynamical system in state space representation is shown in Fig. 3

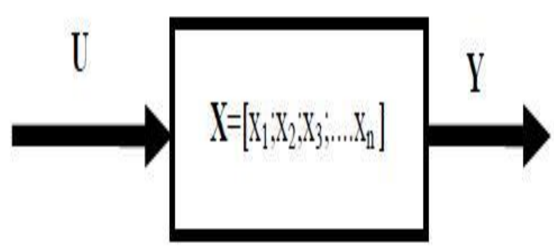

Fig.4: Block diagram representation of a dynamical system

Where **U** is a vector representation of all the possible external inputs to the system, **X** is the state vector containing the system state variables, and **Y** is the output vector containing all the possible system outputs. The state variables of a dynamical system are not necessarily the outputs of the system. Only measurable state variables are referred to as the system outputs and will depend on the number of available sensing devices.

3. SYSTEM MODELLING

A model is a precise representation of a system's dynamics used to answer questions via analysis and simulation. The model we choose depends on the questions that we wish to answer, and so there may be multiple models for a single physical system, with different levels of fidelity depending on the phenomena of interest.

A model is a mathematical representation of a physical, biological or information system. Models allow us to reason about a system and make predictions about who a system will behave. In this text, we will mainly be interested in models describing the input/output behavior of systems and often in so-called "state space" form.

A dynamical system is one in which the effects of actions do not occur immediately. Dynamical systems can be viewed in two different ways: the internal view or the external view.

The internal view attempts to describe the internal workings of the system and originates from classical mechanics. The prototype problem was describing the motion of the planets. For this problem it was natural to give a complete characterization of the motion of all planets. This involves careful analysis of the effects of gravitational pull and the relative positions of the planets in a system.

The other view on dynamics originated in electrical engineering. The prototype problem was to describe electronic amplifiers. It was natural to view an amplifier as a device that transforms input voltages to output voltages and disregard the internal detail of the amplifier. This resulted in the input/output view of systems.

A common class of mathematical models for dynamical systems is ordinary differential equations. Mathematically, an ODE is written as $dx/dt = f(x)$.

3.1 The Heritage of Electrical Engineering

A very different view of dynamics emerged from electrical engineering, where the design of electronic amplifiers led to a focus on input/output behavior. A system was considered as a device that transformed inputs to outputs, as illustrated in Figure 5. Conceptually an input/output model can be viewed as a giant table of inputs and outputs.

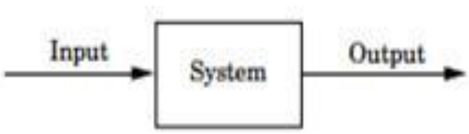

Fig. 5: A system representation

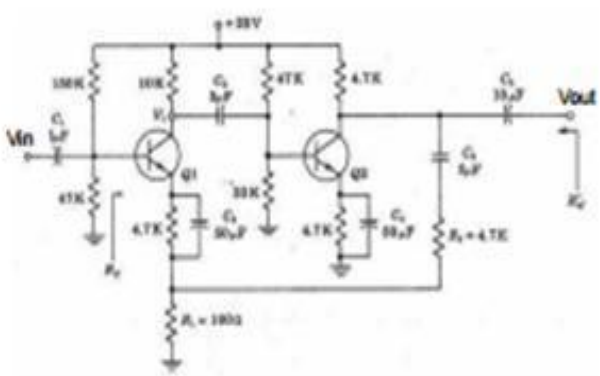

Fig. 6: A system representation with input and output.

3.2 The Control View

When control emerged in the 1940s, the approach to dynamics was strongly influenced by the electrical engineering view. The second wave of developments, starting in the late 1950s, was inspired by mechanics and the two different views were merged. Systems like planets are autonomous and cannot easily be influenced from the outside. Much of the classical development of dynamical systems therefore focused on autonomous systems. In control it is of course essential that systems can have external influences. The emergence of space flight is a typical example where precise control of the orbit is essential. Information also plays an important role in control because it is essential to know the information about a system that is provided by available sensors.

4. INTRODUCTION TO STATE SPACE

State space analysis of control system is based on the modern theory which is applicable to all types of systems like single input single output systems, multiple inputs and multiple outputs systems, linear and non linear systems, time varying and time invariant systems.

- **State in State Space Analysis:** It refers to smallest set of variables whose knowledge at $t=t_0$ together with the knowledge of input for $t \geq t_0$ gives the complete knowledge of the behavior of the system at any time $t \geq t_0$.

- **State Variables in State Space analysis:** It refers to the smallest set of variables which help us to determine the state of the dynamic system. State variables are defined by $x_1(t)$, $x_2(t)$........$X_n(t)$.

- **State Vector** : Suppose there is a requirement of n state variables in order to describe the complete behavior of the given system, then these n state variables are considered to be n components of a vector x(t). Such a vector is known as state vector.

- **State Space:** It refers to the n dimensional space which has x_1 axis, x_2 axis ....x_n axis.

- **State Space Equations**

Let us derive state space equations for the system which is linear and time invariant. Let us consider multiple inputs and multiple outputs system which has r inputs and m outputs.

Where r = u_1, u_2, u_3 .... u_r.

m = y_1, y_2 .... y_m.

Now we are taking n state variables to describe the given system hence n = $x_1, x_2,$ .... x_n. Also we define input and output vectors as, Transpose of input vectors,

$$u(t) = [u_1(t)\, u_2(t)\, u_3(t) \cdots\cdots\cdots u_r(t)]^T$$

Where, T is transpose of the matrix. Transpose of output vectors,

$$y(t) = [y_1(t)\, y_2(t)\, y_3(t) \cdots\cdots\cdots y_m(t)]^T$$

Where, T is transpose of the matrix. Transpose of state vectors,

$$x(t) = [x_1(t)\, x_2(t)\, x_3(t) \cdots\cdots\cdots x_n(t)]^T$$

Where, T is transpose of the matrix.

These variables are related by a set of equations which are written below and are known as state space equations

$$X(t) = Ax(t) + Bu(t) + Ew(t)$$
$$Y(t) = Cx(t) + Du(t) + Fw(t)$$

5. DRIVES WITH CASE STUDIES

Case study 1

ELECTRIC VEHICLE MODELING

For modeling purposes, the recommended EV drive train is as shown in Figure 7. The drive train consists of six components: the electrical motor, power electronics, battery, motor controller, battery controller and vehicle interface. The vehicle interface provides the interface for the sensors and controls which communicate with the motor controller and battery controller. The motor controller normally controls the power supplied to the motor, while the battery controller controls the power from the battery. The battery is for energy storage, usually lithium-ion cells which provide more than 200 V and high current to the power electronics. The power electronics manipulate the voltage, current and frequency provided to suit the motor requirements.

By considering both directions of operation (clockwise and anti-clockwise) and both modes (acceleration and deceleration), the motor’s operation can be described in four quadrants of operation.

This can be visualized by plotting the motor speed and the applied torque on the x–y axis as shown in

Figure 8. The drive train is in motoring mode when the speed and torque values having the same polarity (1st Quadrant & 3rd Quadrant), and in regenerating mode when the speed and torque values differ in polarity (2nd Quadrant & 4th Quadrant). In the 1st Quadrant, with both positive polarities, the motor moves forward, but in the 3rd Quadrant, the motor moves backward. In the 2nd Quadrant, when the torque is positive and speed is negative, the motor is decelerating returning energy to the battery in reverse braking, while in the 4th Quadrant, the energy returns to the battery during forward braking. The battery energy is decreased during motoring mode, but is increased in regenerating mode during regenerative braking when the motor is operating as

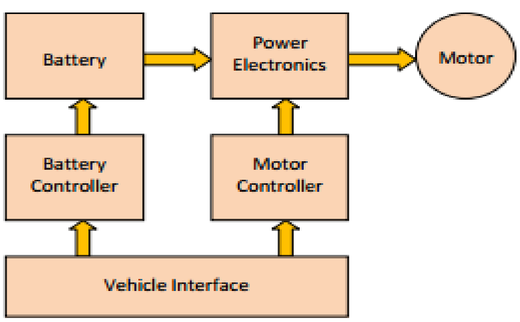

Figure 7. EV Drive Train

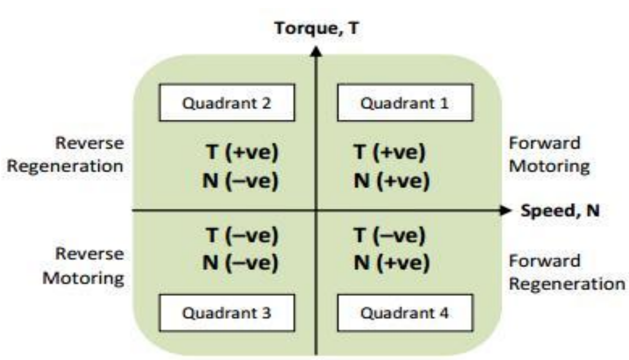

Figure 8. Four Quadrant Drive Operation.

Case Study 2

MODELLING OF PMSM ELECTRIC DRIVES

A number of applications in the mechanical industry require two-coordinate drive systems with good static, dynamic and energetic characteristics. In recent years, permanent magnet synchronous motors (PMSM) have been used in such cases, because they have some advantages, including: compact form; low power loss and high efficiency; high power/mass ratio; good heat dissipation characteristics; low rotor inertia and good dynamics; high speed capabilities.

Applying some control methods, drive systems with such motors can combine the advantages of both DC and AC motor systems. For example, the PMSM electric drives performance improves significantly if their control is executed according to the rotor position. Thus commutation flexibility is provided, avoiding the risk of synchronization failure in case of overload. The complexity of electromechanical systems makes them difficult for description and study in some cases. For this reason, mathematical modeling and computer simulation are widely applied for the purpose of their analysis and synthesis. Such an approach provides for very good conditions to investigate electric drives behavior in various transient and steady-state working regimes, which is not always convenient or possible in industrial and laboratory environments.

5.1 Mathematical modeling of the drive system.

A simplified block diagram of the drive system under consideration is represented in fig. 1, where the notations are as follows: PC – position controller; SC1, SC2 – speed controllers; RC1, RC2

– current reference blocks; CC1, CC2 – three-phase current controllers; IC1, IC2 – inverter control blocks; VI1, VI2 – voltage source inverters; UR – uncontrollable rectifier; C – filter capacitor; PS1, PS2

– position sensors; PF1, PF2 – position feedback blocks; SF1, SF2 – speed feedback blocks; M1, M2 – motors; L1, L2 – loads at the respective coordinate axes; Vsr1, Vsr2 – speed reference signals; Vcr1, Vcr2 – current reference signals; Vpf1, Vpf2 – position feedback signals; Vsf1, Vsf2 – speed feedback signals; Vcf1, Vcf2 – current feedback signals; Vd – DC link voltage; ω1, ω2 – motor speeds; θ1, θ2 – angular positions; Tl1 , Tl2 – load torques applied to the respective motor shafts.

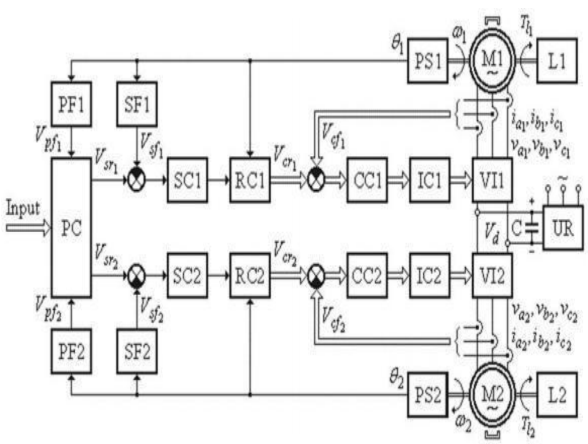

Fig. 9: Block diagram of the drive system under consideration

The motors used are characterized by having permanent magnet-produced fields on the rotors and armature windings on the stators. Both subsystems have identical cascade structures with subordinate regulation. The motors have been controlled in brushless DC motor mode in accordance with the respective rotor positions. Control loops optimization and tuning have been done sequentially, starting from the innermost ones.

6. PREDICTIVE CONTROL IN ELECTRICAL DRIVE SYSTEMS:

Predictive control is a modern control method which pre-calculates the plant's behavior by means of a mathematical model and uses this information to calculate optimum values for the actuating variables via an optimization criterion. The structure of predictive control is presented in Fig.10. The system estimates the unmeasured variables and feeds them back to the prediction block which includes variables prediction and optimization. The optimum values will be output to the actuator and finally control the plant. The basic idea is common for all kinds of predictive control methods, but the specific optimization criterions are different. The figure 11 shows the classifications of MPC.

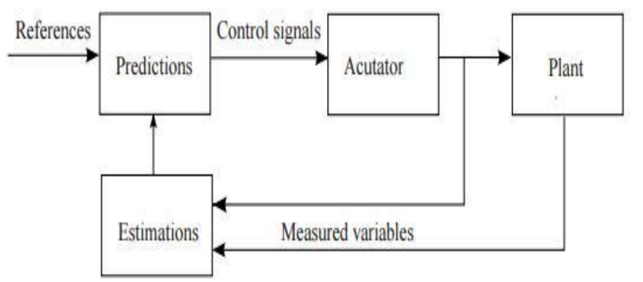

Fig. 10: Block diagram of predictive control method

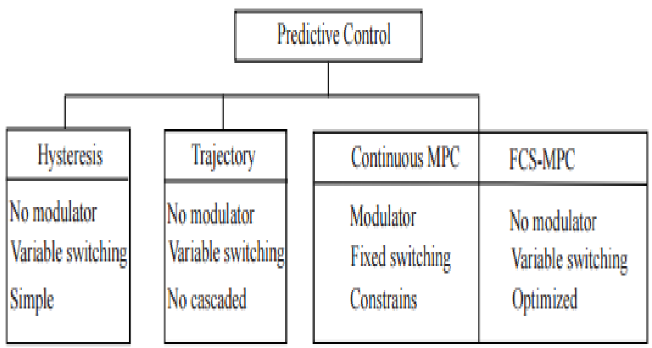

Fig 11 Classification of MPC

7. CONCLUSION & FUTURE WORK

The state space models of the power stages are directly implemented on user defined functions in a simple form. Designing by means of functions and state space equations the models of the power stages allows to the total control on the model and all its variables, being able at any moment to be modified if outside necessary.

An electric drives system plays an important role with recent technologies. But Controlling and modeling are important parameters while designing such a drive system. In this paper a theoretical approach about general drive system and the examples of hybrid electric vehicle drives and modeling of PMSM drive system were discussed. And also how model predictive control is discussed in view of applying control mechanism to a drive system. With this view a new control algorithm will be developed to model an electric drive system.

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