Electromechanical energy conversion

Business, Industries

Introduction Chapter 3 Electromechanical Energy Conversion Topics to cover: 1. Introduction 3. Force and Torque 5. Friction 2. Electro-Motive Force (EMF) 4. Doubly-Excited Actuators 6. Mechanical Components Introduction (Cont.) For energy conversion between electrical and mechanical forms, electromechanical devices are developed. In general, electromechanical energy conversion devices can be divided into three categories: – Transducers (for measurement and control), which transform signals of different forms. Examples are microphones, pickups, and speakers Force producing devices (linear motion devices), which produce forces mostly for linear motion drives, such as relays, solenoids (linear actuators), and electromagnets. – Continuous energy conversion equipment, which operate in rotating mode. A device would be known as a generator if it convert mechanical energy into electrical energy, or as a motor if it does the other way around (from electrical to mechanical). Lorentz Force & EMF Lorentz force is the force on a point charge due to electromagnetic fields. It is given by the following equation in terms of the electric and magnetic fields

F ? q(E? v? B) The induced emf in a conductor of length l moving with a speed v in a uniform magnetic field of flux density B can be determined by a e ? ? v? B? ? dl ? b In a coil of N turns, the induced emf can be calculated by e ? ? Concept map of electromechanical system modeling d? dt where ? is the flux linkage of the coil and the minus sign indicates that the induced current opposes the variation of the field. It makes no difference whether the variation of the flux linkage is a result of the field variation or coil movement. EMF EMF - Example: EMF in a Linear Actuator - Example Solution

Sketch L(x) and calculate the induced emf in the excitation coil for a linear actuator shown below. Assuming infinite permeability for the magnetic core and ignore the fringing effect, we can express the self inductance of the coil as L? x ? ? where Rg ? x? ? N2 ? o N 2 l ? d ? x? ? Rg ? x ? 2g L(x) L(0) 2g ? o ? d ? x? l O is the air gap reluctance. ? e? ? N 2l d? d ? Li ? di dL dx di ? ? L ? i = L? x ? ? i o v 2g dt dt dt dx dt dt EMF - A Single Conductor in a Uniform Field e ? ? I dc If i= Imsin? t , e? Force and Torque - Example Solution (Cont.) If i= Idc , ? o N 2 l 2g ? Im ? Im ? o N 2l 2g

For a single conductor in a uniform magnetic field, we have v ? d ? x ?? I m cos ? t ? vI m sin ? t ? o N l 2 2g ? o N 2 l 2g d Fm ? Il ? B ? o N 2 l In a rotating system, the torque about an axis can be calculated by 2g ?? d ? x ?? cos? t ? v sin ? t ? ? T? r ? Fm v ? ?? ? ? ? d ? x ?? ? ? ? ? d ? x ? 2 ? 2 ? v 2 cos?? t ? arctan? ? where r is the radius vector from the axis towards the conductor. B Fm l I X Force and Torque - A Singly Excited Actuator Consider a singly excited linear actuator. After a time interval dt, we notice that the plunger has moved for a distance dx under the action of the force F.

The mechanical work done by the force acting on the plunger during this time interval is thus dWm ? Fdx Force and Torque - A Singly Excited Actuator The amount of electrical energy that has been transferred into the magnetic field and converted into the mechanical work during dt is dWe ? dWf ? dWm ; dWe ? eidt ? vidt? Ri2dt e ? d? dt ? v ? Ri Because dWf ? dW ? dW ? eidt ? Fdx ? id? ? Fdx e m we obtain From the total differential dW f ? ? , x ? ? ?? ? W f ?? , x ? i? Therefore, ? W f ?? , x ? ?? d? ? and ? W f ?? , x ? ? x F?? dx ? W f ? ? , x ? ? x Force and Torque Force and Torque - A Singly Excited Actuator (Cont.) A Singly Excited Actuator (Cont.) From the knowledge of electromagnetics, the energy stored in a magnetic field can be expressed as ? Wf ? ? , x? ? ? i? ? , x? d? In the diagram below, it is shown that the magnetic energy is equivalent to the area above the magnetization or ? -i curve. Mathematically, if we define the area underneath the magnetization curve as the coenergy (which does not exist physically), i. e. 0 For a magnetically linear (with a constant permeability or a straight line magnetization curve such that the inductance of the coil is independent of the excitation current) system, the above expression becomes 1 ? Wf ? ?, x? ? 2 L? x? and the force acting on the plunger is then F?? ? Wf ? ?, x? ? x 1 ? ? ? dL? x? 1 2 dL? x? ?? ? i 2 ? L? x? ? dx 2 dx ? 2 we can obtain Wf ' ? i, x? ? i? ? Wf ?? , x? ? Wf (? , x) dW f ' ? i , x ? ? ? di ? id? ? dW f ? ? , x ? ? ? di ? Fdx Therefore, ?? ? ? W f ' ? i , x ? ? i ? W f ' ? i , x ? ? i di ? and ? W f ' ? i , x ? ? x F? dx ? W f ' ? i , x ? ? x (? , i) Wf ' (i, x) O i Force and Torque Force and Torque - A Singly Excited Actuator (Cont.) - Example 1 Calculate the force acting on the plunger of a linear actuator as shown below. From the definition, the coenergy can be calculated by i

Wf ' ? i , x? ? ? ? ? i , x? di ? 0 Wf ' ? i, x? ? ? (? , i) Wf (? , x) For a magnetically linear system, the above expression becomes Rg 1 L? x? i 2 2 Ni Wf ' (i, x) Rg and the force acting on the plunger is then F? ? Wf ' ? i , x ? ? x 1 dL? x ? ? i2 dx 2 O i (c) Force and Torque Force and Torque - Singly Excited Rotating Actuator - Solution to Example 1 Assume infinite permeability for the actuator core. The self inductance of the excitation winding can be readily obtained as L? x? ? N 2 ? o N 2l? d ? x? ? 2Rg 2g Therefore, the force acting on the plunger is F? ? Rg Ni ? l 1 2 dL ? x ? 2 i ? ? o ? Ni ? 2 dx 4g

The minus sign of the force indicates that the direction of the force is to reduce the displacement so as to reduce the reluctance of the air gaps. Since this force is caused by the variation of magnetic reluctance of the magnetic circuit, it is known as the reluctance force. Rg The singly excited linear actuator becomes a singly excited rotating actuator if the linearly movable plunger is replaced by a rotor. Through a derivation similar to that for a singly excited linear actuator, one can readily obtain that the torque acting on the rotor can be expressed as the negative partial derivative of the energy stored in the agnetic field against the angular displacement or as the positive partial derivative of the coenergy against the angular displacement. Force and Torque Solution b) Voltage induced - Example • The magnetically-linear electro-mechanical circuit breaker as shown is singly-excited via a N-turn coil. Its magnetic reluctance varies with the angle ? as R ? Rm? ? R0 , where Rm and R0 are constant. • Derive the torque developed by the field from the system co-energy. • When the device is excited with a direct current i= I, the angular displacement increases quadratically as ? ? t ? ? 1 ? t 2 ? ? t ? ? 0 , 2 where ? ? and ? 0 are constant. Find the voltage induced in the coil . Singly Excited Rotating Actuator Total turns, N = N1 + N2 Frame reluctance Rf ? rf 2 Gap reluctance Rg ? 2rg ? ? lf 2? 0 ? r wd 2lg ? 0rd (2? ? ?) , 2? ? 760 ? 1. 33 rad Rg(?) Rcore ? g Rarmature Fm= Ni e(t) ? ? N 2 IRm (? t ? ?) [R0 ? Rm 1 ? t 2 ? ? t ? ? 0]2 2 ? Singly Excited Rotating Actuator ? Singly Excited Rotating Actuator airgap length, lg = 0. 001 m airgap radius, r = 0. 0745 m airgap depth, d = 0. 0255 m frame length lf = 0. 496 m limb width w = 0. 024 m Singly Excited Rotating Actuator ? (?) ? T? ? NI R f ? Rg (?) lf Rf ? 2 ? ? r wd Magnetic flux at equilibrium : ? NI ? 0 ? ? ? R (?) ? R f ? g

? ?? ? ?? ? 0 NI lf 2 ? 0 ? r wd ? lg ? 0rd? ? , Rg ? 2l g ? W f? ?? ? ? ? N2 ? ?, ? R (?) ? R ? f? ? g dRg dRg 2l g sign(?) , where ? d? d? ? 0 rd (2? ? ?)2 1 2 ? L(?) 1 2 ? I ? I 2 2 ?? ?? 122 ? 1 IN 2 ? Rg (?) ? R f ? 2 2l Rr sign(?) 1 ? ? I 2N 2 , where Rr ? g 2 2 ? 0 rd 4 ? Rg (?) ? R f ? (2? ? ?) ? 0 rd (2? ? ?) Restoring Torque ? 1, x ? 0 sign (x) ? ? ?? 1, x ? 0 NI? 0d lf l ? g 2 ? r w r? Force and Torque Singly Excited Rotating Actuator - Singly Excited Rotating Actuator (Cont.) Torque Nm Flux mWb Flux, Torque for 2-pole motor

Energy In g eneral, 1. 5 Coenergy dW f ? id? ? Td ? dW f ' ? ? di ? Td ? ? i W f ? ? , ? ? ? ? i ? ? , ? ? d ? W f ' ? i , ? ? ? ? ? ? i , ? ? di ? W f ? ? , ? ? i? ?? ? W f ? ? , ? ? T?? ?? ? W f ' ? i , ? ? ?? ? i ? W f ' ? i , ? ? T? ?? 0 1. 0 mWb, Nm 0. 5 0 If the permeability is a constant, W f ?? , ? ? ? 0. 0 0 5 10 15 20 25 30 35 40 45 rotor angle 50 55 60 65 70 75 80 1 ? 2 2 L ?? ? 1 ? ? ? dL ?? ? 1 2 dL ?? ? ? i 2 ? L ?? ? ? d ? 2 d? ? ? W f ' ? i , ? ? ? 2 T? T? 12 i L ?? ? 2 1 2 dL ?? ? i 2 d? Force and Torque Force and Torque - Doubly Excited Rotating Actuator - Doubly Excited Rotating Actuator (Cont. If a second winding is placed on the rotor, the singly excited actuator becomes a doubly excited actuator. The general principle for force and torque calculation discussed here is equally applicable to multi-excited systems. The differential energy and coenergy functions can be derived as dW f ? dWe ? dWm where dWe ? e1i1dt ? e2 i2 dt , e1 ? d? 1 dt , e2 ? d ? 2 dt , and dWm ? Td ? Hence, dW f ?? 1 , ? 2 , ? ? ? i1d ? 1 ? i2 d ? 2 ? Td ? ? and ? W f ?? 1 , ? 2 , ? ? ? W f ?? 1 , ? 2 , ? ? ? W f ?? 1 , ? 2 , ? ? d ? 1 ? d ? 2 ? d? ?? 1 ?? 2 ?? ? ? dW f ' ? i1 , i 2 , ? ? ? d i1 ? 1 ? i 2 ? 2 ? W f ? 1 , ? 2 , ? ? ? ? 1 di1 ? ? 2 di 2 ? T d ? ? ? W f ' ? i1 , i 2 , ? ? Therefore, T?? ? i1 di1 ? ? W f ' ? i1 , i 2 , ? ? ? Wf ?? 1 , ? 2 , ? ? ?? ? i2 or di 2 ? T? ? W f ' ? i1 , i 2 , ? ? Force and Torque - Doubly Excited Rotating

Actuator (Cont.) - Example 3 ? ? L? 1 For magnetically linear systems, ? ? 1 ? ? L11 ?? ? ? ? L ? 2? ? 21 L 1 2 ? ? i1 ? L 22 ? ? i2 ? ?? ? ? i1 ? ? ? 11 ? i ? ? ? ? ? 2? ? 21 or ? 1 2 ? ? ? 1 ? ? 22 ? ? ? 2 ? ?? ? The magnetic energy and coenergy can then be expressed as W f ? ? 1 , ? 2 , ? ? ? Therefore, d? ? W f ' ? i1 , i2 , ? ? ?? Force and Torque and ?? 1 1 2 ? 1 1 ? 12 ? 2 2 ? 2 ? ? 1 2 ? 1 ? 2 2 2 W f ' ? i 1 , i 2 , ? 1 1 L 1 1 i 12 ? L i 2 ? L 1 2 i1i 2 2 2 22 2 ? W f ' ? i 1 , i 2 , ? ? ?? ?? 1 2 d L 1 1 ?? ? 1 2 d L 2 2 ?? ? d L 1 2 ?? ? ? i1 ? i2 ? i1i 2 2 2 ?? ?? ?? T?? ? W f ?? ?? 1 , ? 2 , ? ? ? A magnetically-linear doubly-fed electromechanical actuator has two windings and a mechanical output with spatial rotary displacement ?. The self and mutual inductances of the windings are respectively L11 ?? ? ? 5 ? cos(2?) mH, L22 ?? ? ? 50 ? 10 cos(2?) mH, and L12 ?? ? ? L21 ?? ? ? 100 cos? mH. Brushless doubly-fed machine The first winding is supplied with i1 = 1. A while the second winding draws i2 = 20 mA. Determine: a) The general electromagnetic torque of the actuator as a function of ? . b) The maximum torque that the actuator can develop. Solution to Example 3 (a) Solution to Example 3 (cont.) The energy stored at the doubly? fed actuator is, 1 1 2 2 W f ? L11i1 ? L12 i1i2 ? L22 i2 2 2 1 1 ? 3 2 ? 3 2 ? (5 ? cos 2?) ? 10 i1 ? (0. 1cos?)i1i2 ? (50 ? 10 cos 2?) ? 10 i2 2 2 The expression of electromagnetic torque is obtained as follows: ? ? W f (i1 , i2 ,?) T ?? ? i1 ? 1. 5, i2 ? 0. 02 ?? ? 2 2 1 ? (i1 L11) ? (i1i2 L12) 1 ? (i2 L22) ? ? ? 2 ?? ?? 2 ?? 1 1 (1. 5) 2 (? 2 sin 2?) ? 10 ? 3 ? (1. 5)(0. 02)(? 0. 1sin ?) ? (0. 02) 2 (? 20 sin 2?) ? 10 ? 3 2 2 ? 3 ? ? (2. 25 sin 2? ? 3 sin ?) ? 10 Why Magnetic Field? Ratio of Electric and Magnetic Energy Densities in the air gap we ? 0 ? 0 E 2 1 ? ? wm B2 3. 6 ? 10 5 • Saturation Flux Density

Bs = 2T in commonlyused magnetic materials • Air breakdown voltage Ebd= 1, 000, 000 V/m b) At maximum torque, dT ? 0 d? Differentiating T from part (a), 4. 5 cos 2? ? 3 cos ? ? 0 ? 1. 5 cos 2? ? cos ? ? 0 or 1. 5(2 cos 2 ? ? 1) ? cos? ? 0 Solving for ? by the quadratic formula, ? = 55. 94° and 153. 25° (extraneous)

Substituting the value of ? into the torque expression yields, T(max) ? ?(2. 25 sin 2(55. 94) ? 3 sin(55. 94)) ? 10 ? 3 ? ? 4. 57 ? 10 ? 3 Nm Electric Machines • Electric motor converts electrical energy into mechanical motion. • The reverse task, that of converting mechanical motion into electrical energy, is accomplished by a generator or dynamo. • In many cases the two devices differ only in their application and minor construction details, and some applications use a single device to fill both roles. For example, traction motors used on locomotive often perform both tasks if the locomotive is equipped with ynamic brakes. Introduction Electric Motors Electric Machine Insulation Class DC Motors Universal (DC/AC) AC Motors • Induction • Synchronous Stepping Motors Brushless DC Motors Coreless DC Motors Linear Motors MEMS Nano Motors • A critical factor in the reduced life of electrical equipment is heat. The type of insulation used in a motor depends on the operating temperature that the motor will experience. • Average insulation life decreases rapidly with increases in motor internal operating temperatures. • Electric motor converts electrical energy into mechanical motion: Lorentz force on any wire when it is onducting electricity while contained within a magnetic field • Rotor: rotating part • Stator: stationary part • Armature: part of the motor across which the voltage is supplied MaglevMagnetic Levitation Three phase AC induction motors rated 1 Hp (750

W) and 25 W with small motors from CD player, toy and CD/DVD drive reader head traverse DC Generators / Dynamos AC Generators / Alternators As the first electrical generator capable of delivering power for industry, the dynamo uses electromagnetic principles to convert mechanical rotation into a pulsing direct electric current through the use of a commutator.

Without a commutator, the dynamo is an example of an alternator, which is a synchronous singly-fed generator. With an electromechanical commutator, the dynamo is a classical direct current (DC) generator. The DC generator can operate at any speed within mechanical limits but always outputs a direct current waveform. Mechanical energy is used to rotate the coil (N turns, area A) at uniform angular velocity ? in the magnetic field B, it will produce a sinusoidal emf in the coil: Permanent Magnet DC Generators d? d ? ? (NBA cos ?) dt dt ? NBA? sin ? t e(t) ? ? http://micro. magnet. fsu. edu/electromag/java/generator/dc. tml Automotive alternator Rotor emf and current are induced by rotating magnetic field http://micro. magnet. fsu. edu/electromag/java/generator/ac. html Mechanical Components Mechanical Components - Mass and Inertia The mechanical component which stores kinetic energy is a mass in a translational system, and a moment of inertia in a rotational system. - Mass and Inertia (Cont.) The kinetic energy stored by a mass moving at a velocity v, or a moment of inertia rotating at an angular speed ?. can be calculated by ? x M T F J Wk ? 1 Mv2 2 d? d 2? T? J 2 ? J dt dt dv d 2x F? M ? M dt 2 dt 1 J? 2 2 (translational system) rotational system) Comparing with the relationships of voltage, current, and magnetic energy in an inductor: V? L By the Newton’s second law, we have Wk ? or di dt and WL ? 1 Li2 2 we may regard a mass or a moment of inertia as an inductor which stores magnetic energy, if we let J? L M? L or Mechanical Components Mechanical Components - Springs An ideal spring is a device with negligible mass and mechanical losses, whose deformation is a single-valued function of the applied force or torque. A linear ideal spring has deformation proportional to force or ? 1 torque. - Springs (Cont.) For a given distortion of x and ? the potential energy stored in a spring is 1 1 W p ? ? Td ? ? K ? 2 W p ? ? Fdx ? Kx 2 T x1 F ? K ? x 1 ? x o ? ? Kx (linear spring) (torsional spring) Comparing with the relationships of electric charge, voltage and electric energy in a capacitor: Q V? C F 2 2 WC ? and 1 1 Q2 VQ ? 2 2C we may regard a spring as an electric capacitor which stores electric potential energy, if we let T ? K ?? 1 ? ? o ? ? K ? K? 1 C Friction Friction Modelling Friction: force that opposes the relative motion or tendency of such motion of two surfaces in contact. Friction between the two objects converts kinetic energy into heat.

Coefficient of friction (Frictional coefficient): dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together, needs not be less than 1 - under good conditions, a tire on concrete may have a coefficient of friction of 1. 7. Static friction (stiction) occurs when the two objects are not moving relative to each other: Rolling friction occuring when one object " rolls" on another (like a car's wheels on the ground), is stiction as the patch of the tire in contact with the ground, at any point while the tire spins, is stationary relative to the ground.

Kinetic (or dynamic) friction occurs when two objects are moving relative to each other and rub together: – Sliding friction is when two objects are rubbing against each other. – Fluid friction is the friction between a solid object as it moves through a liquid or a gas. The drag of air on an airplane or of water on a swimmer are two examples of fluid friction. Lu-Gre Model (1995): ? 0 , ? 1 bristles' stiffness and damping coefficient ? 2 viscous friction FC , F S Coulomb and Stribeck friction ? F f ? ? 0 z ? ? 1z ? ? 2v ? z? v? v z g (v) 2 1 g (v) ? [FC ? (F S ? FC) e ? v / v S)] ? 0 Mechanical Components Mechanical Components - Damper The mechanical damper is analogous to electrical resistor in that it dissipates energy as heat. An ideal damper is a device that exhibits no mass or spring effect and exerts a force that is a function of the relative velocity between its two parts. A linear ideal damper has a force proportional to the relative velocity. In all cases a damper produces a force that opposes the relative motion of the two parts. Mechanical friction occurs in a variety of situations under many different physical conditions.

Sometimes friction is unwanted but must be tolerated and accounted for analytically, as, for example, in bearings, sliding electrical contacts, and the aerodynamic drag on a moving body. In other cases friction is desired and is designed into equipment. Examples are vibration dampers and shock absorbers. d ? x2 ? x1 ? dt dx ? B dt F? B ? B? R d ?? 2 ? ? 1 ? dt d? ? B dt T? B - Damper (Cont.) Mechanical Components Mechanical Components - Damper (Cont.) The damping due to Coulomb friction, as shown by the characteristic, can be regarded as a nonlinear resistor, which can keep the voltage across it to be constant.

The Coulomb friction force can be expressed as - Damper (Cont.) There is another kind of damping caused by the drag of a viscous fluid in turbulent flow. 2 F ? ? Bs d x2 ? x1 dt F ? ? d Fn ? ? d Fn d ? x2 ? x1 ? dt ?? ? ? ? Bs dx dt d ? x2 ? x1 ? dt ? ?? 2 ? R ? B s dx dt dx dt ? dx dt or T ? ? Bs d ?? 2 ? ? 1 ? dt Comparing with V= RI, we may conclude that ? F R? d n dx dt ? ? ? Bs d? dt ? ? 2 2 ? R ? B s d ? dt MR Dampers as a semi-active device MR Damper New Models Non-symmetrical Model (2007) ? F (x) ? c0 x ? ko (x ? x0) ? ? z ? ? ? z ? (? ? (? ? ? sign(zx) z) x n : hysteresis variable, ? , ? , ? , ? , n, c0 , k0 : model parameters Bouc-Wen Model: ? F (x) ? c0 x ? k o (x ? x0) ? ? z ? ? ? ? z ? ? ? z | x || z | n ? 1 ? ? x | z | n ? ? x z: hysteresis variable , ? , ? , ? , ? , n , c 0 , k 0 : model parameters Static Hysteresis Model (2006) ? F (x) ? cx ? kx ? ? z ? f 0 ? z ? tanh(? x ? sign(x)) z : hysteresis variable, ? , ? , f 0 , c, k : model parameters Minimally-Parameterised Model (2007) ? F : G (x) ? D (x), F (x) ? ? 1 ? F2 : G (x) ? D (x), b G (x) ? a ? ? 1 ? exp (cx) ? D (x) ? rexp{? (x / 2?) 2 } ?? ? 0 x ?? ? 0, x