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Energy Analysis of LVRM Actuator

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Abstract: *In this paper energy analysis of LVRM actuator is demonstrated. Linear Variable Reluctance Motor Actuator (LVRM) is a modification of Switched Reluctance Motor.The motor with transverse magnetic flux consists of a primary part, which is moving and a secondary part which is stationary and does not have any windings. The motor can operate under AC or DC supply . When supplied from an AC source it must be equipped with a capacitor connected in series with the coil. In this case the motor operates on the basis of resonance in an RLC primary circuit. When supplied from a DC source it must be equipped with a controlled switch connected to the primary circuit.Design calculations were focused on determining the resistance, the inductance and the mass of the primary part .The concept of Co-Field energy ,is also demonstrated .*
Keywords: *Field Energy,**Co-Field Energy, LVRM, Reluctance,SRM***

I. INTRODUCTION

A reluctance motor is an electric motor in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximized [3] .A switched reluctance motor (SRM) is simple in construction compared to induction or synchronous machines. A linear motor can be defined as being the result of a cylindrical rotary electric machine, which has been mentally split along a radial plane, unrolled and flattened[1].The result is an electrical machine in which the primary and the secondary are linear and parallel as shown in Figure 1.1. In contrast to a rotational electric motor, a linear motor generates a linear force (thrust force) along its length, i.e. there is no torque or rotation is produced by the relationship between electric currents and magnetic field. By supplying suitable currents to the primary with a suitable excitation in the secondary of a linear motor, they will move relatively in a linear path. This makes linear motors have a number of advantages over rotational motors in linear motion. Linear switched reluctance machines are an attractive alternative due to the lack of windings on either the stator or translator structure. The windings are concentrated rather than distributed making them ideal for low cost manufacturing and maintenance. Further, the windings are always in series with a switch so that, in case of a shoot-through fault, the inductance of the winding can limit the rate of change of rising current and provide time to initiate protective relaying to isolate the faults. Moreover, the phases of the linear switched reluctance machine areindependent and in case of one winding failure, uninterrupted operation of the motor drives ispossible though with reduced power output [4]. These advantages enable the linear switchedreluctance machine drives to operate as an economical high performance system with better failsafereliability. The linear switched reluctance machines are the counterparts of the rotatingswitched reluctance machines .

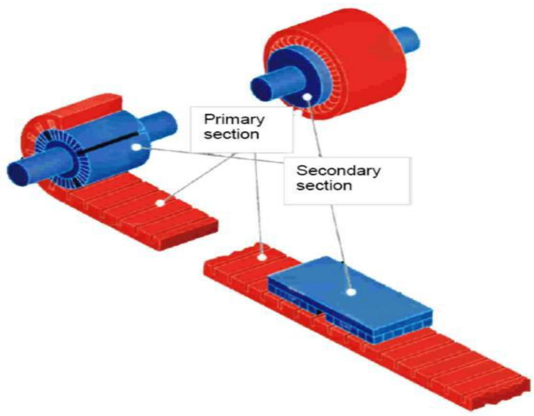

Figure 1.1 Imaginary process of splitting and unrolling a rotary machine to produce a linear motor [81]

Fig 1.1a Proposed LVRM Actuator

II. MAGNETIC ENERGY ANALYSIS OFLVRM ACTUATOR

In an electromagnet [5] the current is generated by the magnetic field. To determine the magnetic field energy stored in the motor let the electromagnetic structure shown inFig. 1.2 be considered. It consists of primary part, which does not move and the secondary part that can move and does not have the winding.Assuming that the secondary part does not move, the instantaneous voltage across the terminals of a single-phase SRM winding is related to the flux linked in the winding by Faraday's law,

$$V = i R + \frac{d\lambda}{dt} \quad (1.1)$$

V- terminal voltage , i-phase current , λ- flux linkage

R-resistance

The flux linkage in an SRM varies as a function of rotor position θ and the motor current i. Thus equation can be represented as

$$V = i R + \frac{d\lambda}{di}\frac{di}{dt} + \frac{d\lambda}{d\theta}\frac{d\theta}{dt} \quad (1.2)$$

$\frac{d\lambda}{di}$is defined as winding inductance L(θ,i) which is a function of rotor position and current . Multiplying both sides of equation by electrical current i ,gives the expression for instantaneous power in LSRM .

$$V = i^2 R + i\frac{d\lambda}{dt} = i^2 R + i\frac{d\lambda}{di}\frac{di}{dt} \quad (1.3)$$

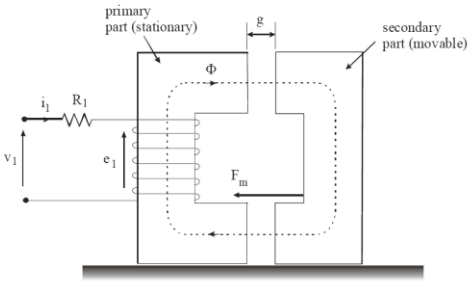

Figure 1.2 Illustration of field energy of LSRM

The left hand side of the above equation denotes the electrical power P_e delivered to LSRM . The firs term on the right hand side represents the ohmic losses and the second term represents the electrical power at coil terminal which is the sum of mechanical output and any power stored in LSRM

.

$$P_e = L\frac{dI}{dt} i \quad (1.4)$$

Relation between Power and Energy is

$$\frac{dW_e}{dt} = P_e \quad (1.5)$$

Where W_e denote total energy delivered to winding which is the sum of energy stored in the coil W_f and energy converted to Mechanical work W_m done .

$W_e = W_f + W_m$ (1.6)

Magnetic field energy $W_f = \int_0^{\lambda} i \, d\lambda$ (1.7)

The energy stored in the Magnetic field with air gap ' g' can be expressed I terms of magnetic flux density B_g as

$W_f = \int \frac{B_g}{\mu_0} \mathrm{d}B_g . V_g = \frac{B_g}{2\,\mu_0} V_g$ (1.8)

The field energy is inversely proportional to permeability and directly proportional to volume of air gap .

The area below the curve in fig 1.3 is defined as magnetic Co- field energy . Co-field energy$W_f^{'}$ is defined by

$W_f^{'} = \int_o^{i} \lambda . \, di$ (1.9)

If λ - i is nonlinear then $W_f^{'} > W_f$

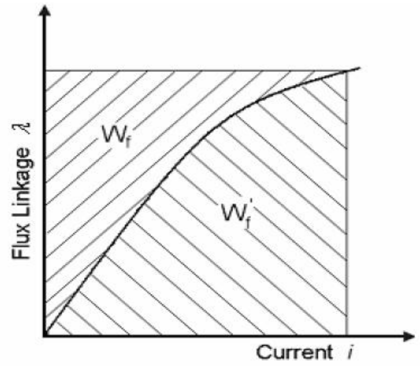

Fig 1.3 Graphical Interpretation of magnetic field energy

Consider Fig 1.2 if secondary part is moved slowly then current remains the same at both positions because coil resistance does not change and voltage is said to be a constant.

The operating point has moved slowly from point a → b (fig 1.4) .

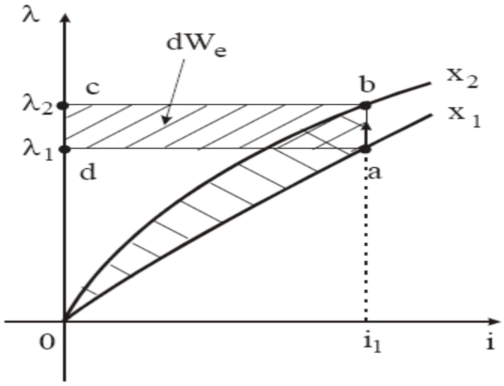

Fig 1.4 Illustration to magnetic force derivation

During the motion increment electric energy has to be send to system

$dW_e = \int e . i \, dt = \int_{\lambda_1}^{\lambda_2} i \, d\lambda$ = area (a b c d) (1.10)

The field energy has been changed by this increment :

$dW_f =$ area (O b c –O a d) (1.11)

The Mechanical energy ,

$dW_m = dW_e - dW_f$
= area (a b c d) + area (O a d) – area (O b c) (1.12)
= area (O a b)

is equal to mechanical work done during the motion of secondary part and is represented by the shaded area in fig 1.4 . This shaded area can also be seen as increase in Co- Energy :

$dW_m = dW_f^{'}$ (1.13)

Since :

$dW_m = f_m$ dx (1.14)

The force f_m that is causing differential displacement is :

$f_m = \frac{\partial W_{f\ (i,x)}^{'}}{\partial x}$i = constant (1.15)

In a linear system coil inductance L linearly varies with the primary position for a given current .Thus for an idealized system :

λ = L (x ,i) I (1.16)

Since the Co-field energy is given by Eq (1.9) after inserting the value of λ from Eq (1.16) into Eq (1.9) we obtain :

$W_f^{'} = \int_0^i L(x,i).di = \frac{1}{2}\ L(x)i^2$ (1.17)

The Magnetic force acting on the secondary part is obtained from Eq (1.15) and Eq (1.17) .

$f_m = \frac{\partial}{\partial x}\ (\frac{1}{2}\ L(x)i^2\ = \frac{1}{2} i^2 \frac{dL(x)}{dx}$ (1.18)

For a linear system field energy is equal to Co–field energy

$W_f = W_f^{'} = \frac{1}{2}$ L(x) i^2 (1.19)

If the primary part of the reluctance motor is an electromagnet we can use Eq (1.18) to determine the force acting on secondary part.

There is another force attractive force f_y which can be expressed in terms of magnetic flux density B_g .

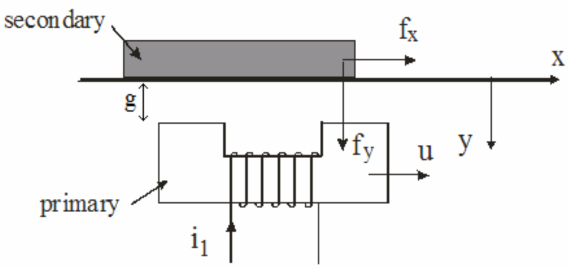

Fig 1.5 Force components in a reluctance motor

The relation between current number of turns and field intensity is given by :

N i $= H_g$ 2g = $\frac{B_g}{\mu_0}$ 2g (1.20)

$i = \frac{B_g}{N\,\mu_0}\ 2g$ (1.21)

The coil inductance L depends on the reluctance of magnetic circuit which is given by :

$L = \frac{N^2\ \mu\ \ A_m}{g}$ (1.22)

from equations 1.17 , 1.19 and 1.21 we obtain

$W_f^{'}\ = \frac{B_g^2}{2\,\mu_0} A_g\ 2g$ (1.23)

from equation 1.15 and 1.23 we obtain

$f_y\ = \frac{\partial}{\partial g}(\frac{B_g^2}{2\,\mu_0}\ \ A_g 2g\ ) = \frac{B_g^2}{2\,\mu_0}\ \ 2A_g$ (1.24)

CONSTRUCTION OF A 1ϕ LVRM ACTUATOR

A single phase variable reluctance motor with U shaped primary core is considered . The motor consists of a primary part that possess winding and secondary part .The winding of primary is supplied with voltage v which causes a current to flow .The current produces a magnetic flux ϕ that flows through a closed path that is perpendicular to the direction of motion (x axis) [9] .

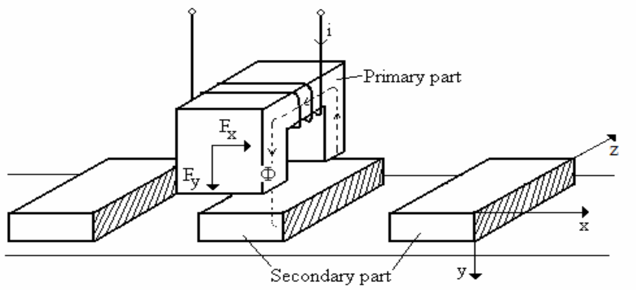

Fig 1.6 Single phase linear reluctance motor with U shaped primary core

The primary part is affected by two forces a propulsive force f_x and attractive force f_y.The linear propulsive force is expressed as

$f_x\ = \frac{1}{2} i^2 \frac{dL(x)}{dx}$ (1.25)

L(x) denote coil inductance which is expressed as a function of x coordinate . The higher the value of $\frac{dL(x)}{dx}$ stronger the propulsive force .

The inductance of the primary coil is expressed as a function that depends on the shape of primary and secondary core .For the construction show above it may be approximated by the function

$L = L_m \left[1 + \cos\left(\frac{\pi}{l}\ x\right)\right] + L_{min}$ (1.26)

Shown graphically in Fig 1.7

$L_m = \frac{L_{max}\ -\ L_{min}}{2}$ (1.27)

The force that is proportional to $\frac{d\,L(x)}{dx}$ is not only changing in value but also in its direction which is seen in derivative of inductance .

$\frac{dL(X)}{dx} = (-)\ L_m \sin\left(\frac{\pi}{l}x\right) . \frac{\pi}{l}$ (1.28)

When the position of the centre of the primary is at (-x_1)
$\frac{dL(x)}{dx}$is positive and force is positive . The primary placed between the middle of the secondary elements is not affected by any force , the same is the case when primary comes in full alignment with the secondary .

The primary is always affected by an attractive force

$$f_y = \frac{B_g^2}{2\,\mu_0} A_g \qquad (1.29)$$

B – magnetic flux density ,A_g– air gap area

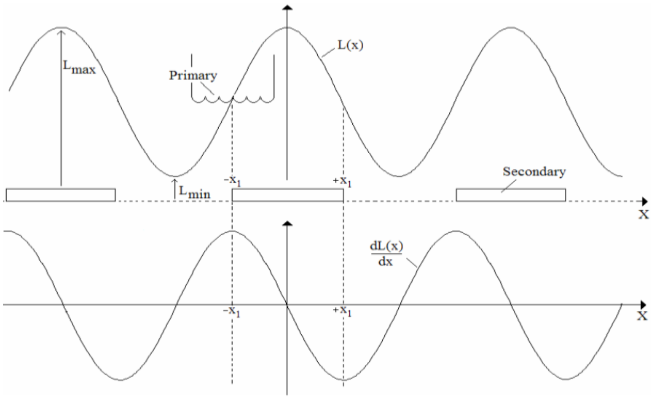

Fig 1.7 Inductance and derivative of inductance changing

1V MODES OF OPERATION

A) AC SUPPLY

LVRM actuator operates from AC source using the principle of resonance in RLC circuit of primary part . The primary part moves with respect to secondary in x-direction .During the motion coil inductance L changes since it depends on the position of primary part with respect to secondary part . The middle of primary coil is placed at distance (- x_1) (see Fig 1.8) and inductance of the coil is equal to L(-x_1) (see Fig 1.9) . Since the force acting on the primary part is f_m = 0.5 $i^2 \frac{dL(x)}{dx}$ and the derivative $\left(\frac{dL(x)}{dx}\right)$at x =$x_1$ is positive it will be pulled to the middle (x=0) of the secondary element .Due to the inertia of primary part it moves to the edge of the secondary part . During its movement it experiences a negative force beyond '0' point but this braking force is less than driving force , which the primary experiences before '0' point .The resultant effect is that primary part is leaving the secondary part and approaching the next secondary part where it is again driven to the positive direction of x-axis . [7]

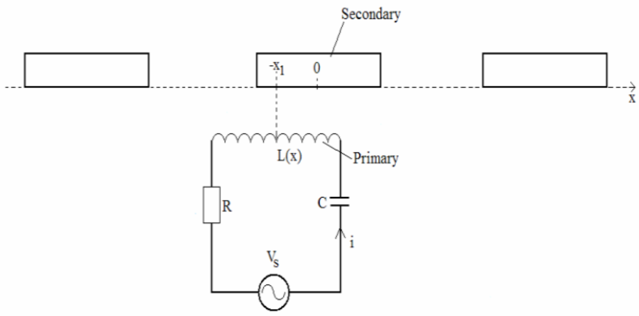

Fig 1.8 LVRM supplied from an AC source

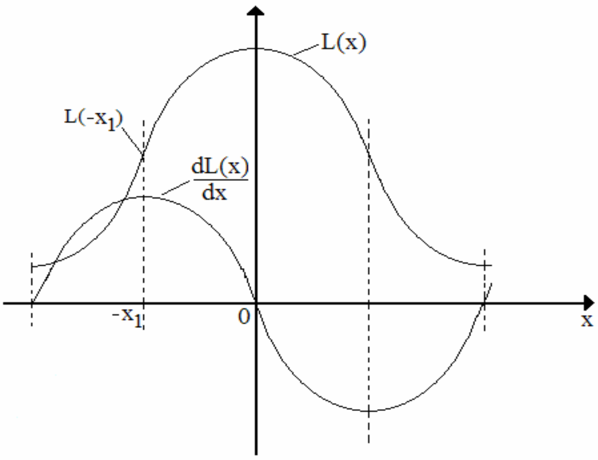

Fig 1.9 Inductance and derivative of inductance waveforms

To increase the driving force a capacitor C is connected in series with the primary part .The value of capacitor is chosen there to give resonance in R-L-C circuit , at position (-x_1) (see Fig 2.0)) a heavy current flows , the primary is pulled towards '0' point with a strong force . The resultant effect is that primary gets a strong " kick" at a place when resonance occurs , moving the actuator more effectively in x- direction .The capacitance at a particular position can be defined by using resonant condition formulae

$$C = \frac{1}{2\,\pi\, f^2\ \ L\,(x_1)}$$

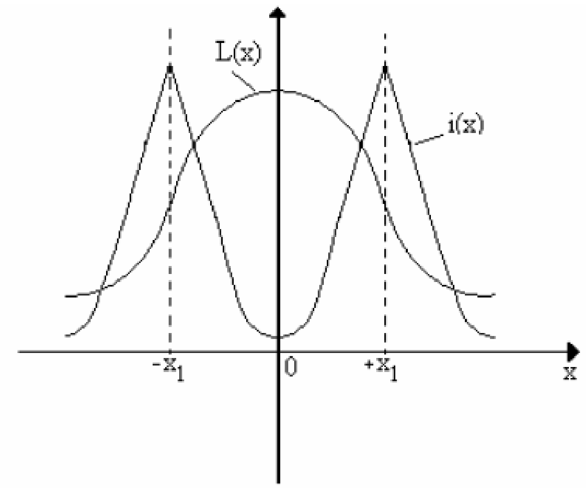

Fig 2.0 Inductance and resonance current as a function of displacement x

B) DC SUPPLY

To improve the performance of LVRM energise the primary part when it is affected by a force in positive direction ($\frac{dL\,(x)}{dx}$ $is\ positive$ – see Fig 1.9) , that is when the primary moves from the edge (position -x_1) to the centre point '0' .This of course requires the application of a controlled switch which would switch the primary part ON and OFF at its particular position with respect to secondary. It means motor must be equipped with a switching circuit instead of a capacitor . (see fig 2.1)

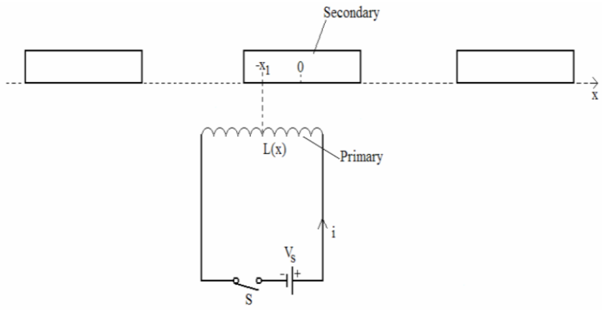

Fig 2.1 LVRM actuator with DC source

An LVRM actuator with DC supply is shown in Fig 2.2Power MOFET can be used as a switch .When MOSFET turns on full voltage appears across the motor and inductance of coil winding causes current to flow through the coil . When MOSFET turns OFF energy stored in the inductance of motor winding forces diode into conduction . During this time current is ramping down .Fig 2.3 shows two modes of operation under DCsupply condition .The diode allows magnetic energy stored in the coil to be released after switching off . [11]

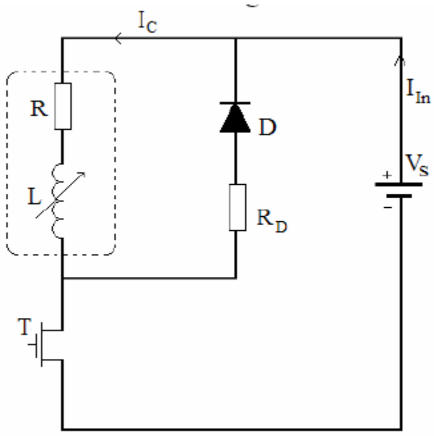

Fig 2.2 Circuit diagram of a linear reluctance motor under DC supply

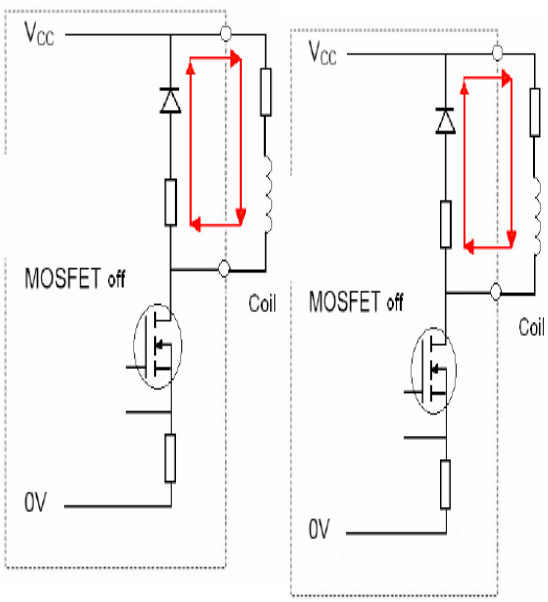

Fig 2.3 Switch control (a) MOSFET conduction cycle (b)Diode fly back conduction cycle

V. Conclusion

The energy analysis single phase LVRM actuator was presented in this paper .LVRM work on the principle of Co- field energy which is found to be greater than magnetic field energy , considering non-linear magnetisation characteristics . It could operate both on AC supply and DC supply . The advantage of LVRM is that linear motion is obtained directly ,no rotary to linear conversion is required. Hence the frictional losses that occur in commonly used rotary to linear energy conversion mechanisms such as lead –screw ,chain drive and belt drive is avoided.

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References

[1] P. Khong, R. Leidhold and P. Mutschler. “Magnetic guidance of the mover in a long-primary linear motor,” Industry Applications, IEEE Transactions – electronic publishing, DOI: 10.1109/TIA.2011.2125934, March 2011.

[2] P. Khong, R. Leidhold and P. Mutschler. “Magnetic guidance of the mover in a long-primary linear motor,” in ECCE 2009. IEEE, San Jose, CA Sept. 2009, pp. 2354–2361

[3] P. Khong, R. Leidhold and P. Mutschler.“Magnetic guiding and capacitive sensing for a passive vehicle of a long-primary linear motor,” in EPE/PEMC 2010, Ohrid-Macedonia, Sept. 2010, pp. S3-1 – S3-8.

[4] R.Krishnan, R.Arumugam, James F. Lindsay, “Design procedure for switchedreluctancemotors”, IEEE Trans. on industry applications, Vol. 24, No.3, 1988.

[5] Bae,Han-Kyung,Byeong-SeokLee, Praveen Vijayraghavan, and R.Krishna, “Linearswitched reluctance motor: converter and control”, in Conf. Rec. of the 1999 IEEE IAS Ann. Mtg., Oct. 1999, Phoenix, AZ, pp. 547-554.

[6] T. Kenjo and S. Nagamori, “Permanent-magnet and brushless DC motors”,Clarendon Press, Oxford, 1985

[7] E.A. Mendrela, “Comparison of the performance of a linear reluctance oscillatingmotor operating under AC supply with one under DC supply”, IEEE Trans. 0nenergy conversion, Vol. 14, No.3, September 1999

[8] E.A. Mendrela, “Comparison of the performance of a linear reluctance oscillatingmotor operating under AC supply with one under DC supply”, IEEE Trans. Onenergy conversion, Vol. 14, No.3, September 1999

[9] R. Krishnan. “Propulsion with and without wheels.” in IEEE International Conference on Industrial Technology (ICIT), vol. 1, no. 2, 2005, pp. 11–19.

[10] T. Masuda, M. Yoshikawa, M. Tawada. “Formulation of elevator door equation of motion.”JSME International Journal Series Dynamics Control Robotics Design and Manufacturing, vol. 39, no. 2, pp. 279–285, 1996.

[11] P. Mutschler. Class lecture, Topic: “Control of Drives.” Institute of Power Electronics and Control of Drives, TU Darmstadt, Sep. 2004