# Advanced Control of Soft Starters for Industrial Drives

## *Power Electronics Control Problems and Applications in Industry*

*Dr.-Ing. Peter Magyar, GE-ADE, Hella KGaA Hueck & Co., Germany*


***The 4th IEEE GCC Conference and Exhibition***
***Manama, Kingdom of Bahrain***
***11-14 November 2007***

HELLA
*Ideas today for the cars of tomorrow*

# Agenda

- Soft Starter Introduction
  - Circuit layout examples
  - Appliances
- Operation Modes
  - Soft starter mode of operation
    - Current balancing
    - Comparison of symmetrical and asymmetrical firing angle setting
  - Contactor mode of operation
    - Transients of asynchronous motors
    - Asynchronous direct on-line (DOL) switching
    - Comparison of various DOL switching processes
- Soft Starter Applications
  - Benefits
  - Application examples

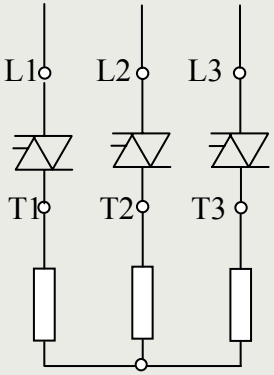
- Soft Starters are electronic starters designed to accelerate, decelerate and protect induction motors by voltage control
- The control of voltage applied to the motor, by means of thyristors‘ firing angle variation, allows smooth starting and stopping
- With proper adjustment it is possible to optimise the motor starting process, so that
  - starting current and
  - instantaneous torque due to the transient offset in the motor flux linkage

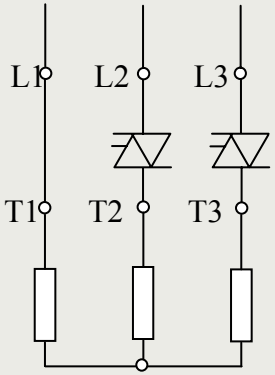
  remains as low as possible

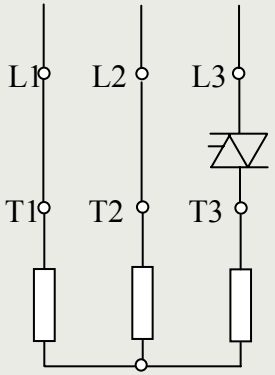
- Typical applications
  - Industrial / Commercial / Residential
  - Main modes of operation
    - Soft starters for electrical / mechanical saving purposes
    - Qiuck DOL starters for fast and trouble-free start-up

# *Advanced Control of Soft Starters for Industrial Drives*

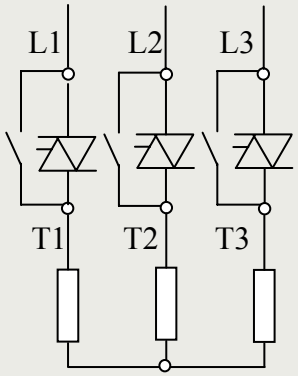
## *Soft Starter Circuit Layout Examples*

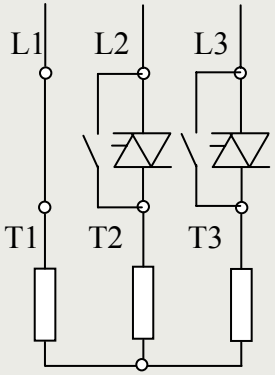


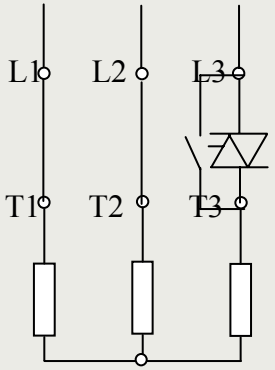




The semiconductor switches are active both in transient and steady-state mode of operation



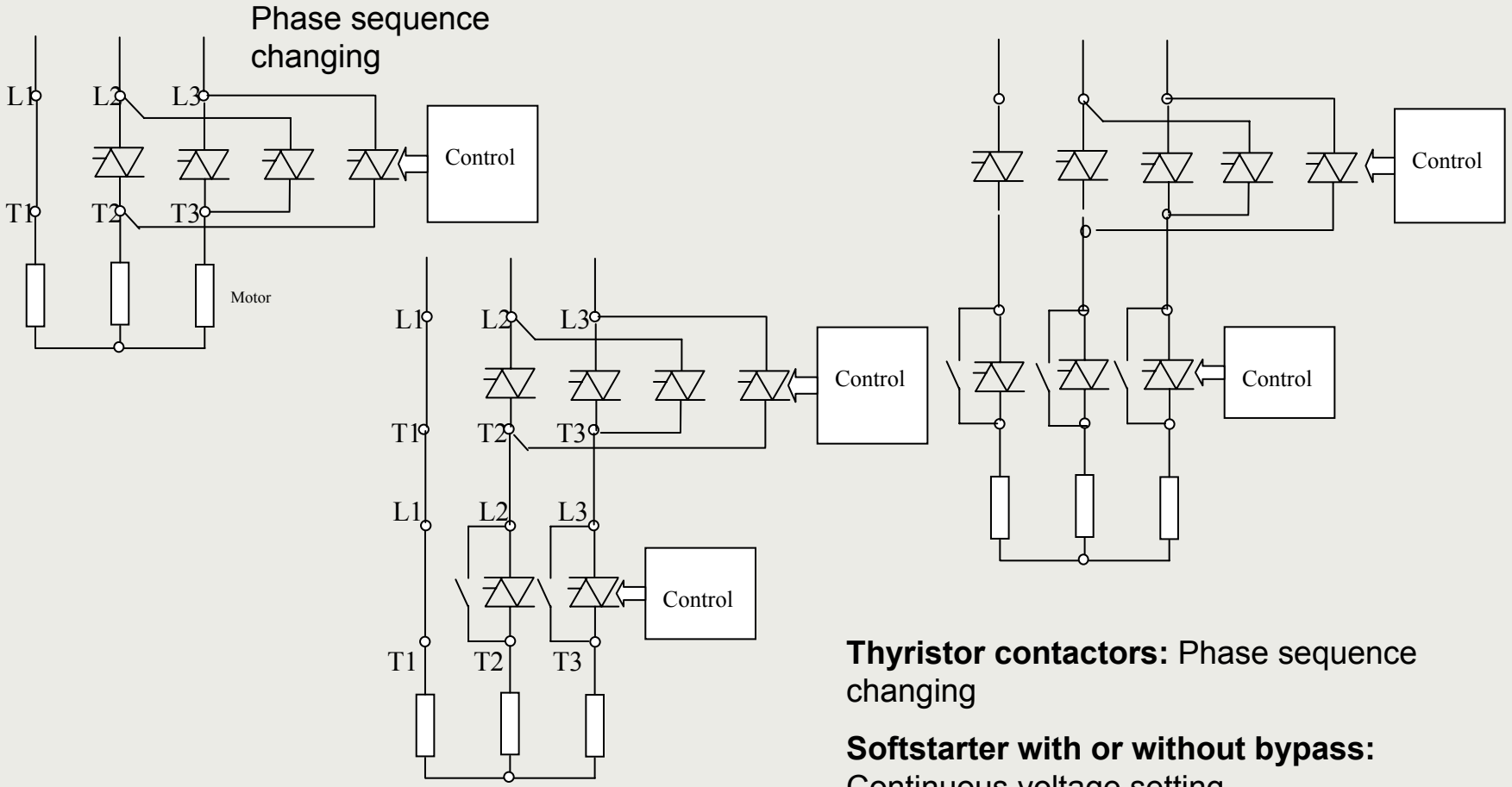




The semiconductor switches are active in transient mode of operation, the bypass contactors in the steady-state one

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft Starter Circuit Layout Examples*




**Thyristor contactors:** Phase sequence changing

**Softstarter with or without bypass:** Continuous voltage setting

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft Starter Appliances*

150kW, 500kW
500V+10%

90kW, 500V

55kW, 500V


11/2.2kW 22/4kW 30/7.5kW

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft Starter Appliances*

Replacing mechanical contactors

Modular design: soft starter & contactor

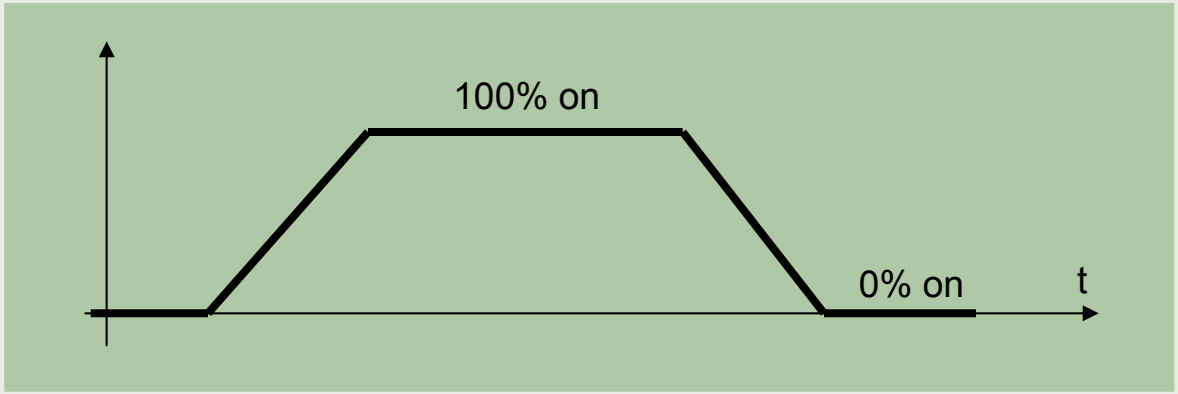
Meets the standard

IEC/EN 60947 (Semiconductor AC Motor Controllers and Starters)

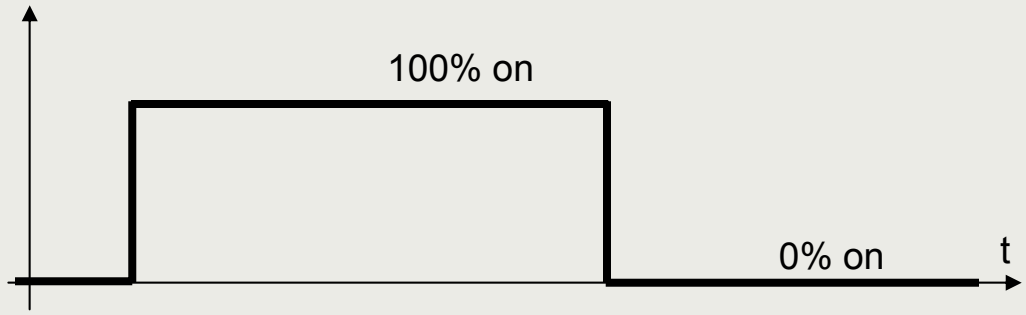
# *Advanced Control of Soft Starters for Industrial Drives*

## *Mode of Operations: Soft Starter and Contactor*

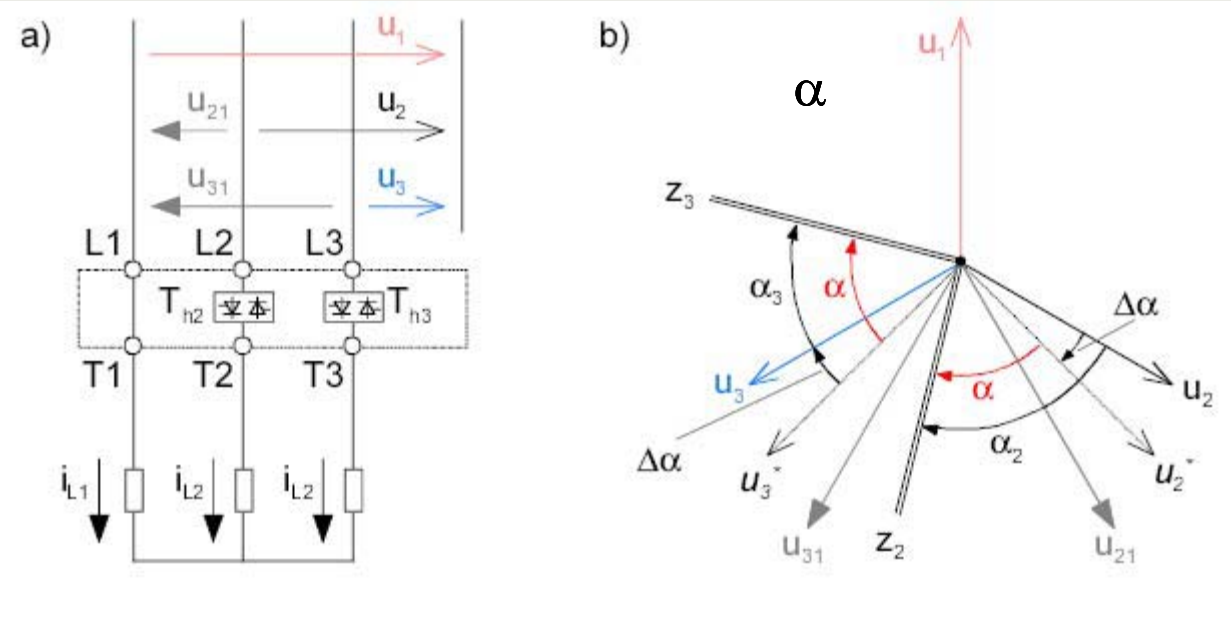
- Output voltage level v. time
  - Soft starter




  - Contactor



- Continuous firing angle setting
  - symmetrical firing angle, $\alpha$
  - asymmetrical firing angle, $\alpha_2 = \alpha + \Delta\alpha, \quad \alpha_3 = \alpha - \Delta\alpha$

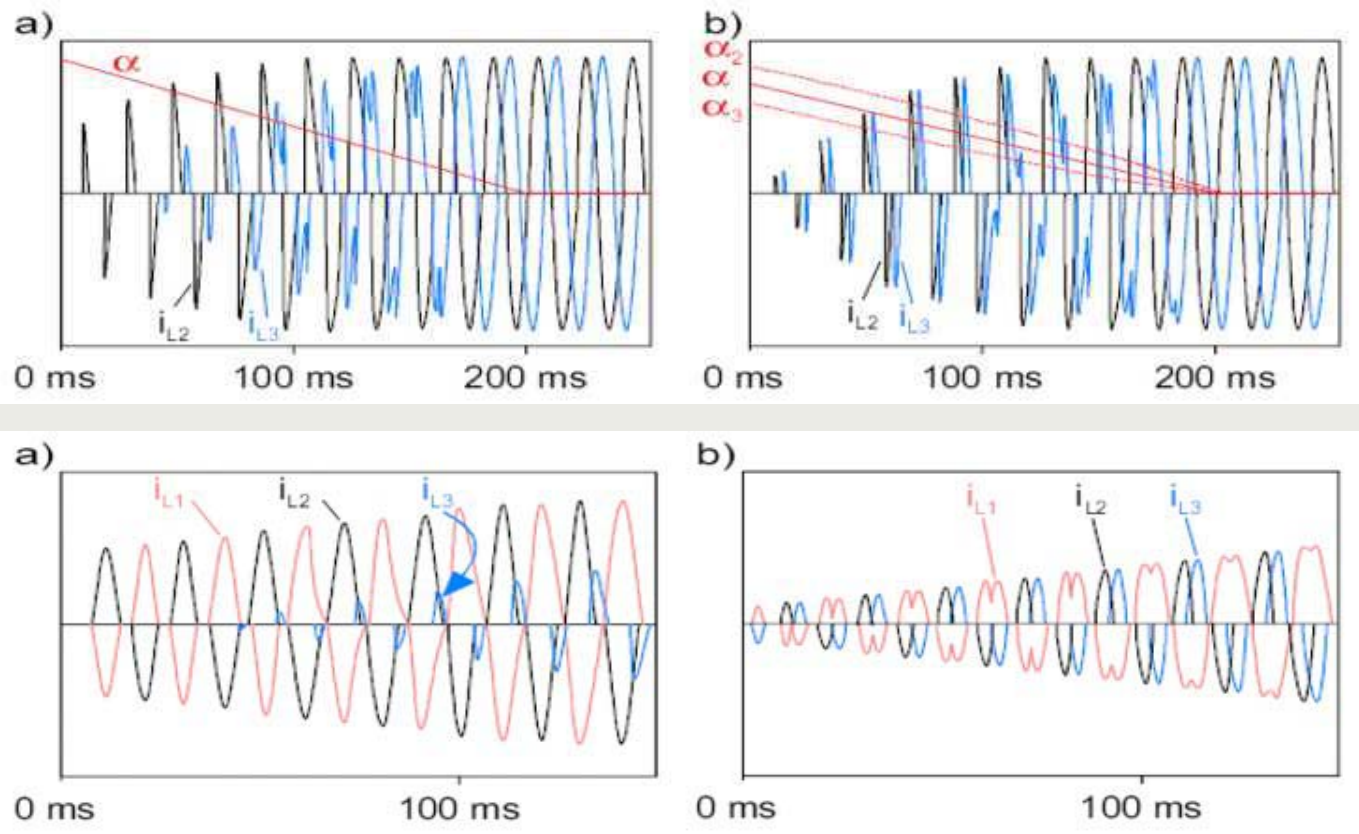



Start Pspice

View Circuit


Dr.-Ing. Peter Magyar, Hella KGaA Hueck & Co, Germany

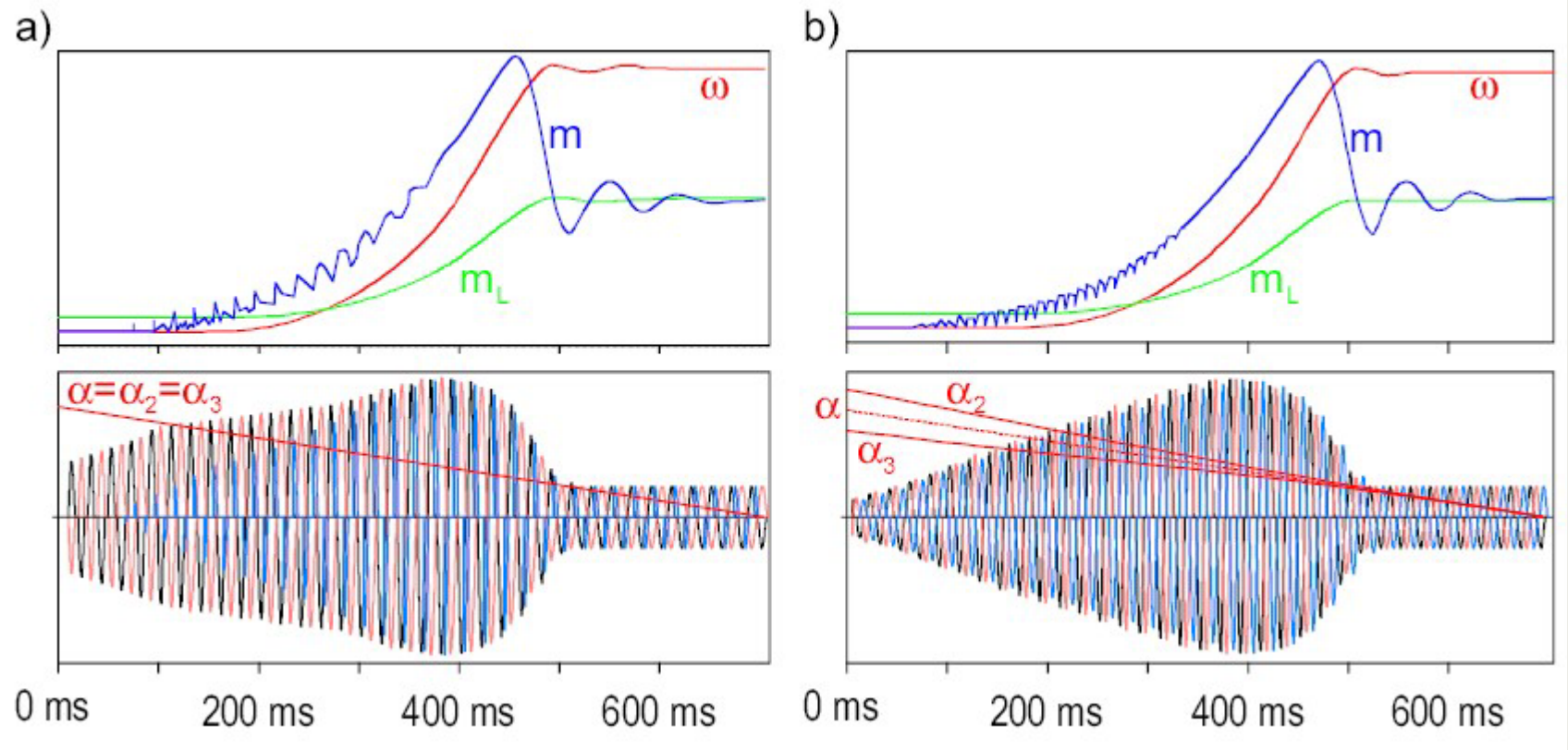
- Continuous firing angle setting
  - a) symmetrical, b) asymmetrical firing angle $\Rightarrow$ current balancing
  - resistive and motoric load





Dr.-Ing. Peter Magyar, Hella KGaA Hueck & Co, Germany

- Continuous firing angle setting
  - a) asymmetrical, b) symmetrical firing angle $\Rightarrow$ current balancing
  - soft starting of an 11 kW ASM





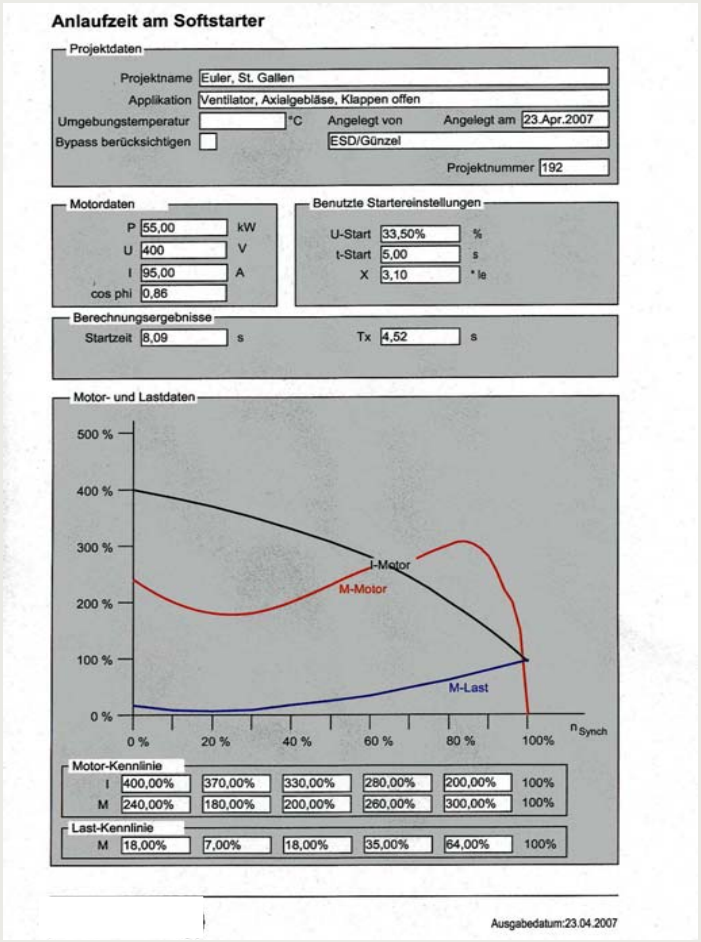
Dr.-Ing. Peter Magyar, Hella KGaA Hueck & Co, Germany

# *Advanced Control of Soft Starters for Industrial Drives*

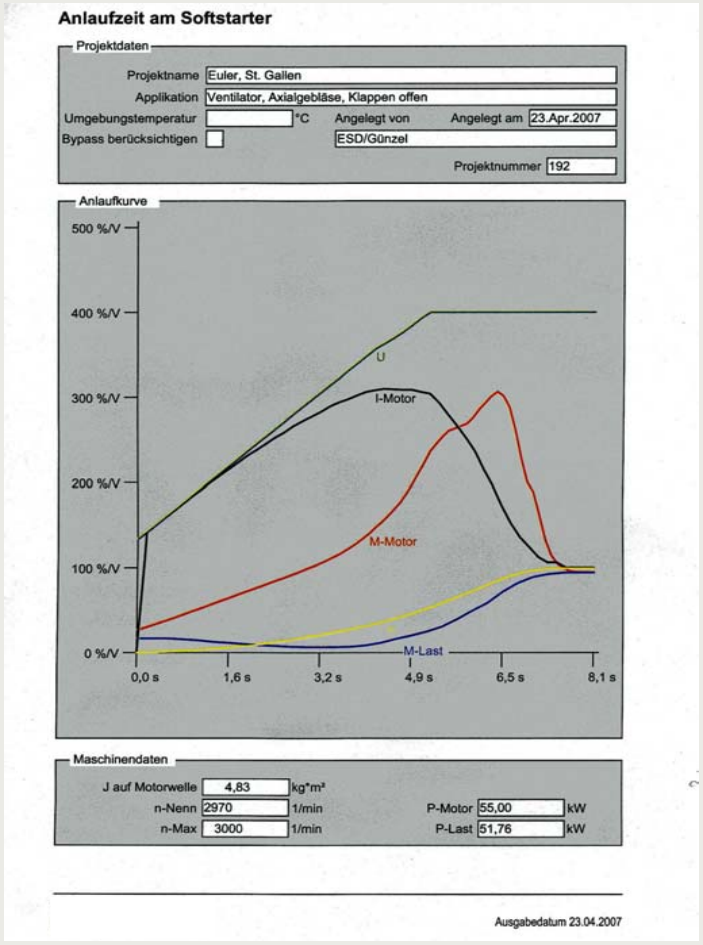
## *Soft Starter Industrial Application*

- 55kW ventilator drive

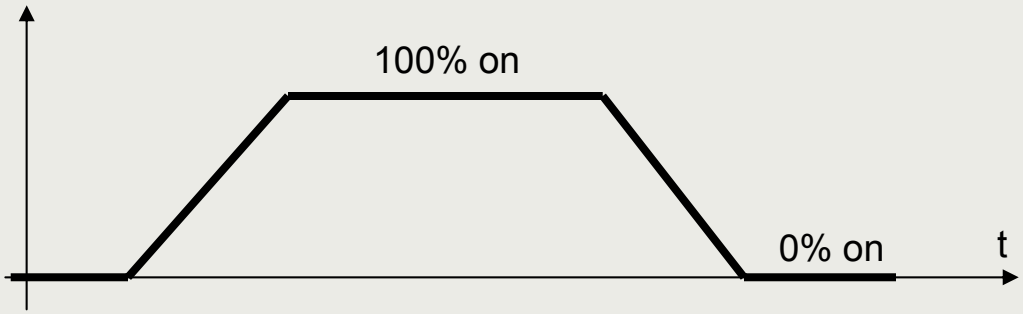
Data Sheet



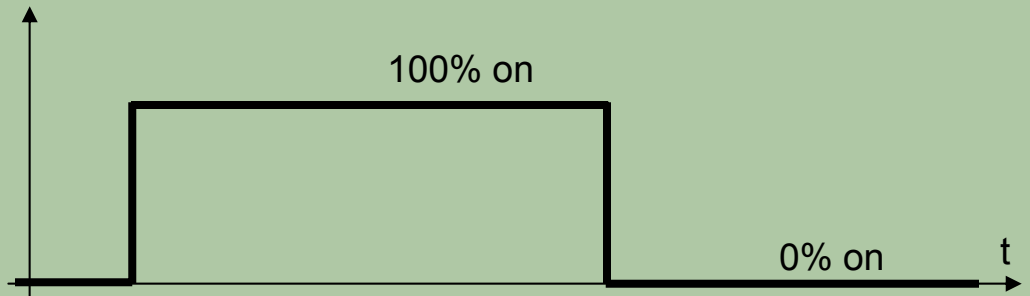

Soft Start-up



- Output voltage level
  - Soft starter

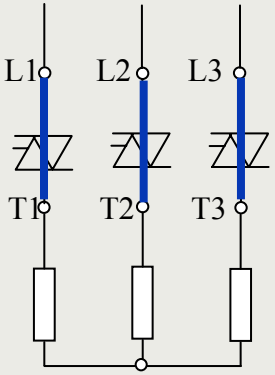


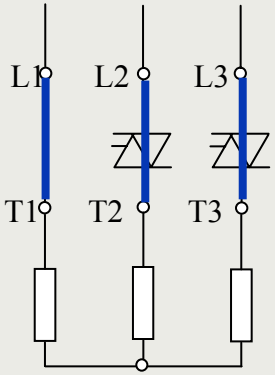

  - Contactor

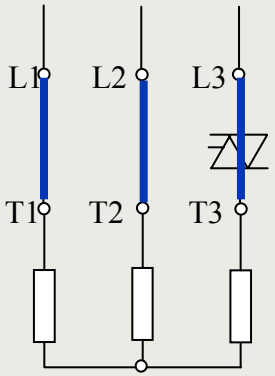


# *Advanced Control of Soft Starters for Industrial Drives*

## *Synchronous and Asynchronous Switch-On*



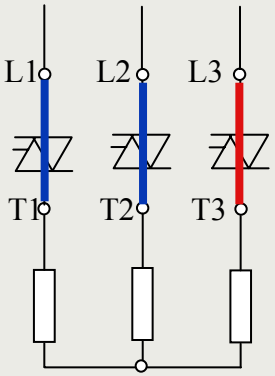



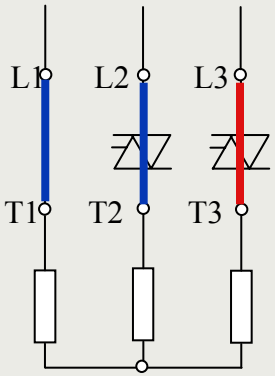

**c-mode of operation:**

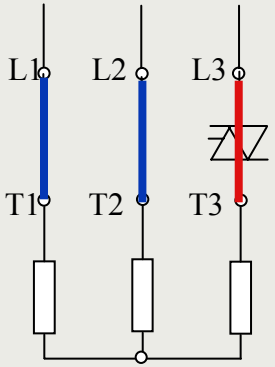
All switches are „on“

OR

-Synchronous switching




**n-mode of operation**:

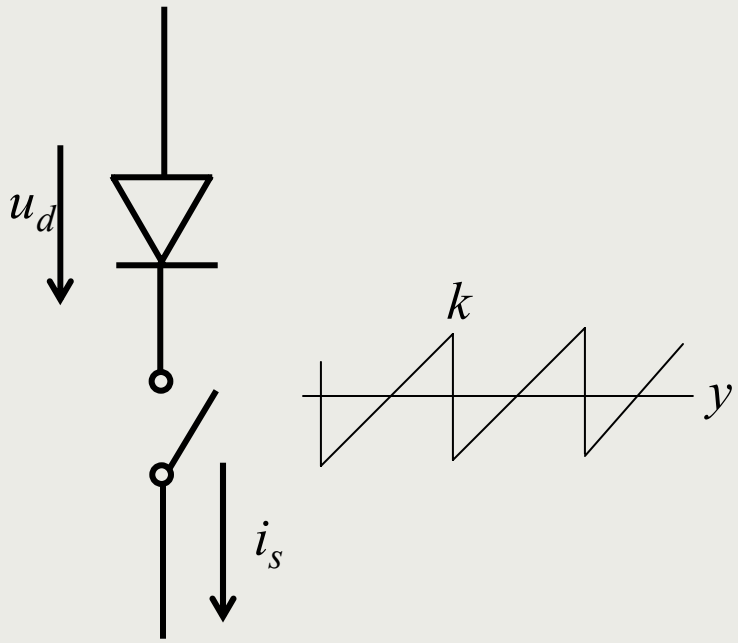
One switch is „off“

OR

-Asynchronous switching

- Characteristics of PES in relation to the controllability of PSD
  - PES are characterized by the switching processes of power semiconductor devices (PSDs)
  - PSD can be considered as ideal switches
    - device operation will not obscure the basic operation of the circuit
    - the important converter operation will be clearly understood and depends only on the topology and controllability of the switches
  - Presently available PSDs can be classified into three groups according to their degree of controllability
    - Fully-controllable (transistor-type) switches: both on- and off-state will be generated by control system signals
    - Semi-controllable (thyristor-type) switches:
      - on-state is signal generated triggering („firing“) by gate signal
      - off-state is caused by decreasing the current to zero („extinction“) by power circuit voltage (latching)
    - Diode-type switches:
      - on-state is power voltage generated
      - off-state is current „extinction“

- Characteristics of switching processes



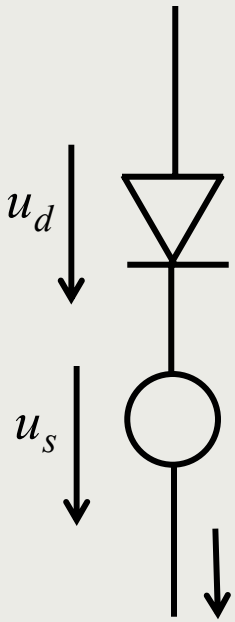

Switch on criteria

$$u_d = 0$$

$$k - y = 0$$

Switch off criteria

$$i_s = 0$$




On-state:

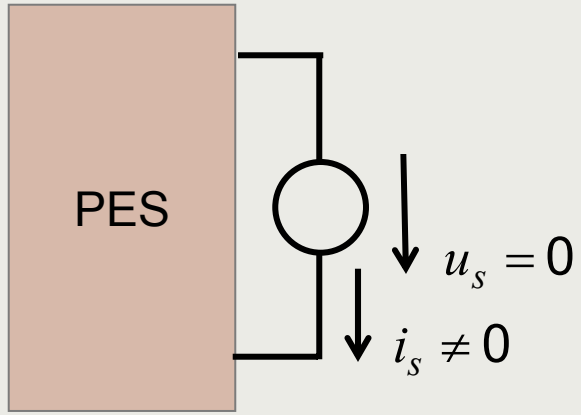
$$u_s = 0$$

Off-state:

$$u_s = u_s(i_s = 0)$$

- Mathematical model of PES for on- an off-state caused by one switch

On-state

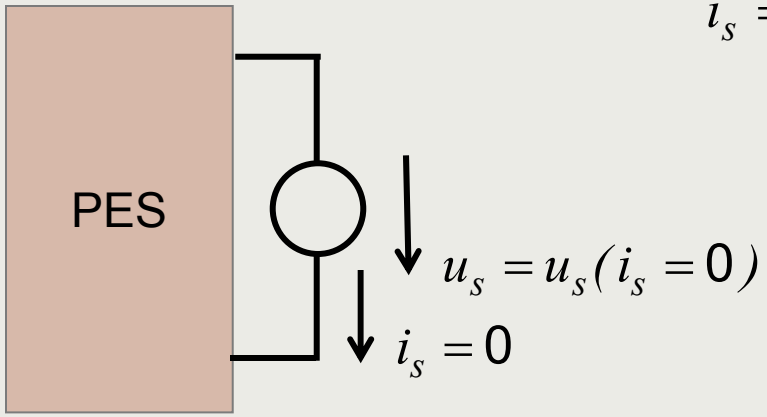



$$\dot{x} = f(x,u) + gu_s$$

$$u_s = 0 \quad \Rightarrow \quad \dot{x} = f(x,u)$$

$$i_s = k^T x$$

Off-state




$$\dot{x} = f(x,u) + gu_s$$

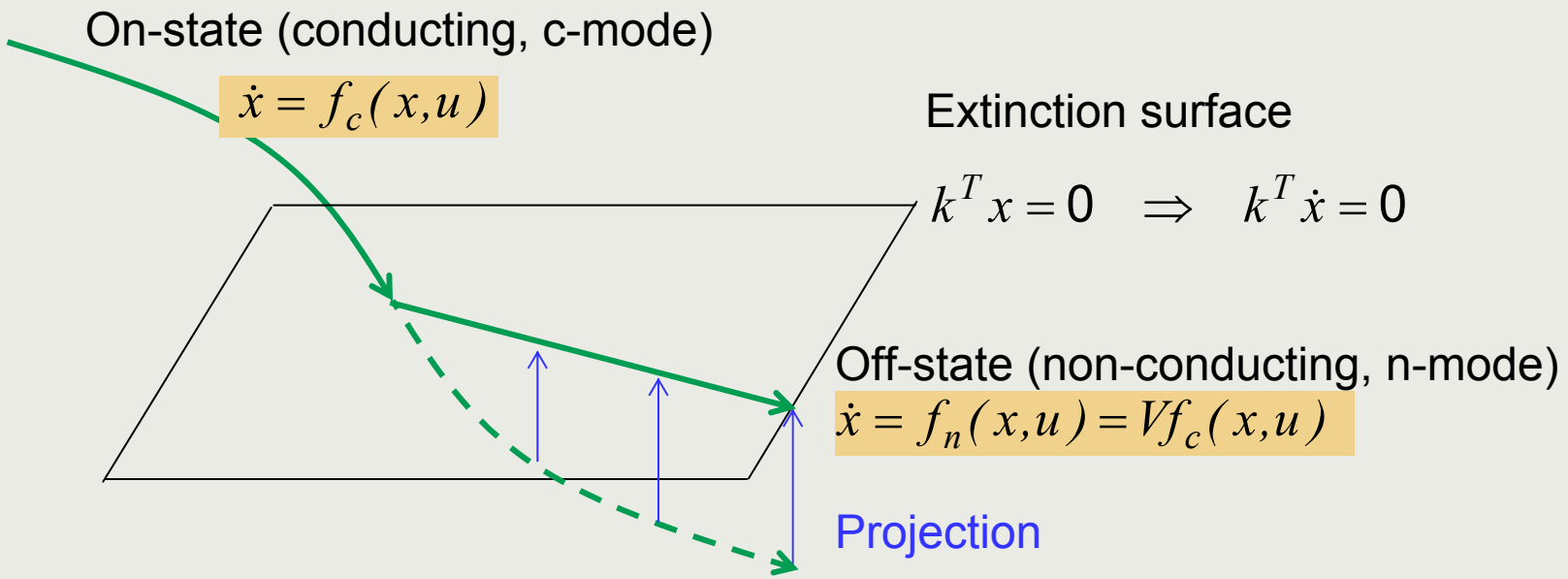
$$i_s = 0 \quad \Rightarrow \quad 0 = k^T x = k^T \dot{x}$$

$$0 = k^T (f(x,u) + gu_s)$$

$$u_s = -\frac{k^T f(x,u)}{k^T g} \quad \Downarrow$$

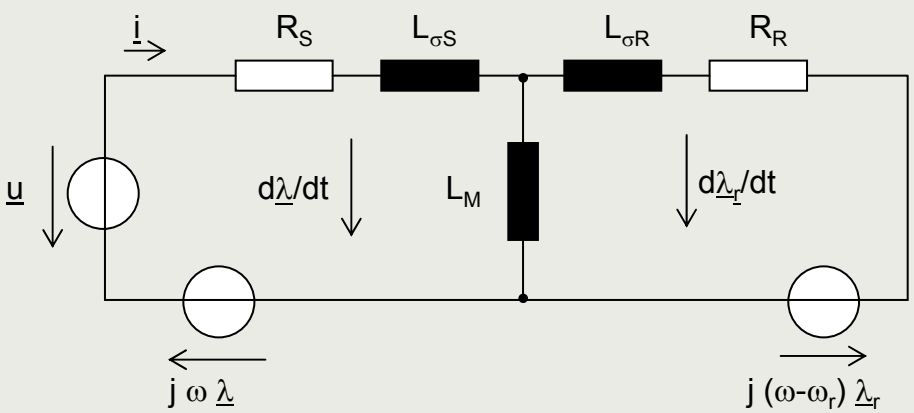
$$\dot{x} = Vf(x,u) \qquad V = I - \frac{gk^T}{k^T g}$$

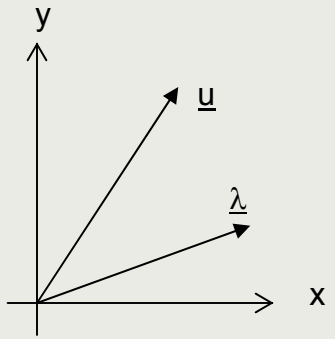
- Model of the PES



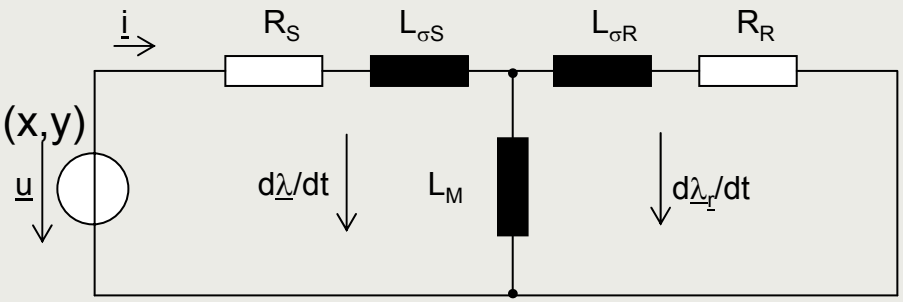

- The n-state is a „projected state“ of the previous c-state
  - The matrix of projection is: V
  - Important rule: the behaviour of the system in a non-conductive mode is *projection of the behaviour in the previous c-mode*

- Equivalent circuit with voltage and flux linkage phasors

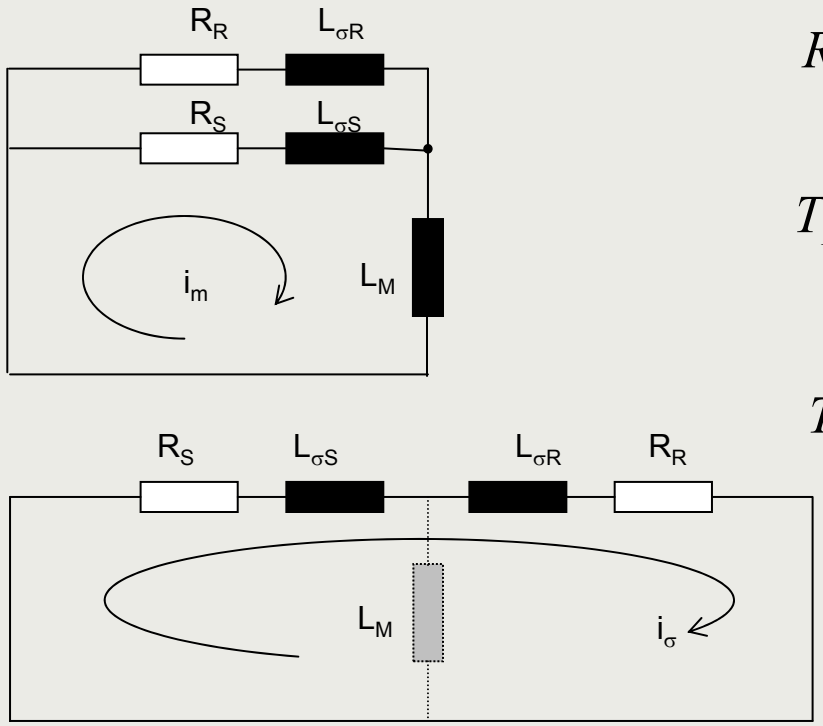



- Equivalent circuit at standstill
  - Properties
    - 4th order sytem
      - two vector components (x,y)
      - two independent meshes in conjunction with both components



- Two characteristic current paths in both directions each
  - magnetisation path
  - leakage path




Approx.

$$R_S \approx R_R \quad L_{\sigma S} \approx L_{\sigma R} \quad L_{\sigma S,R} << L_M$$

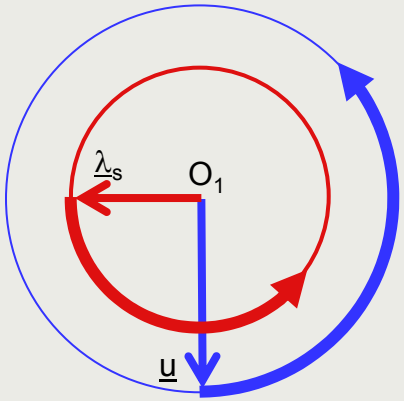
$$T_M = \frac{L_M + \frac{L_{\sigma S,R}}{2}}{\frac{R_R}{2}} = \frac{2L_M + L_\sigma}{R_R} \approx 2T_{R0}$$

$$T_\sigma \approx \frac{2L_{\sigma S,R}}{2R_{S,R}} = \frac{L_{\sigma S}}{R_S} = T_{\sigma S}$$

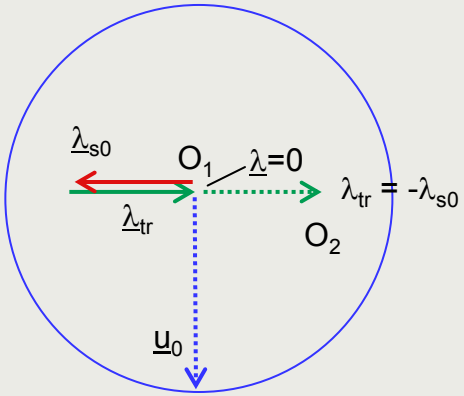
$T_M \Rightarrow$ slow transients

$T_\sigma \Rightarrow$ fast transients

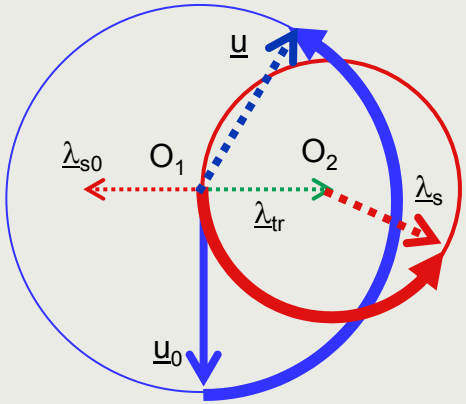
- Transient voltage and flux linkage phasor trajectories due to 3-phase synchronous switch-on




Steady-state 3-phase mode of operation




Flux linkage transient due to 3-phase switch-on




Flux linkage transient mode of operation

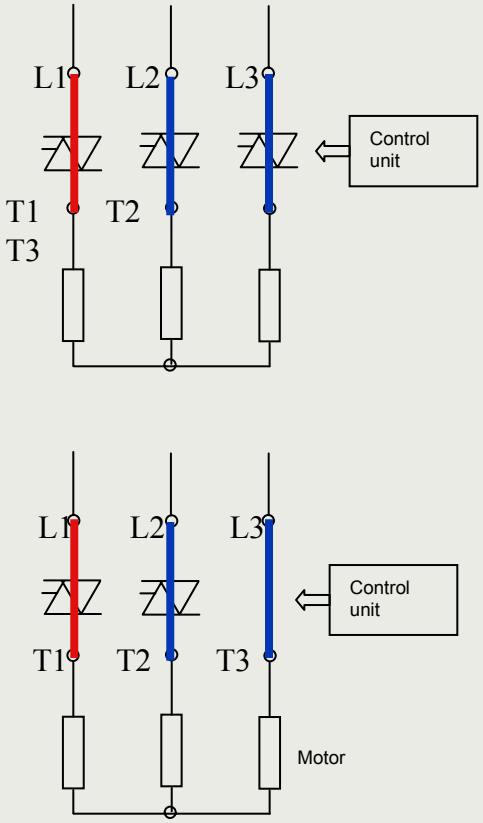
Time constant: $T_M$

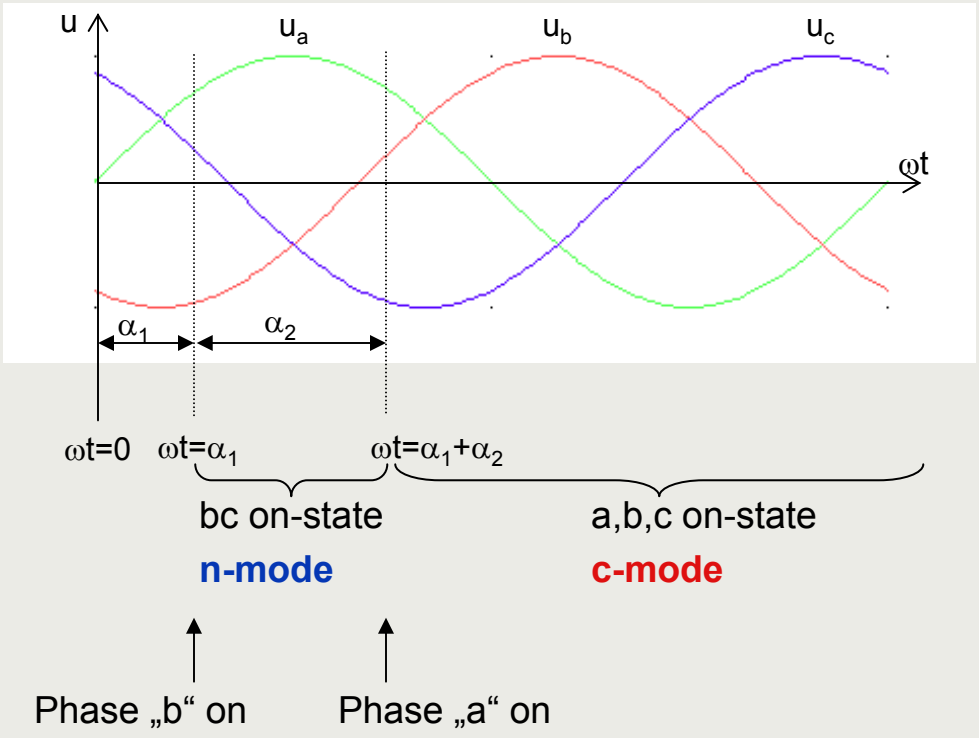
page 25

# *Advanced Control of Soft Starters for Industrial Drives*

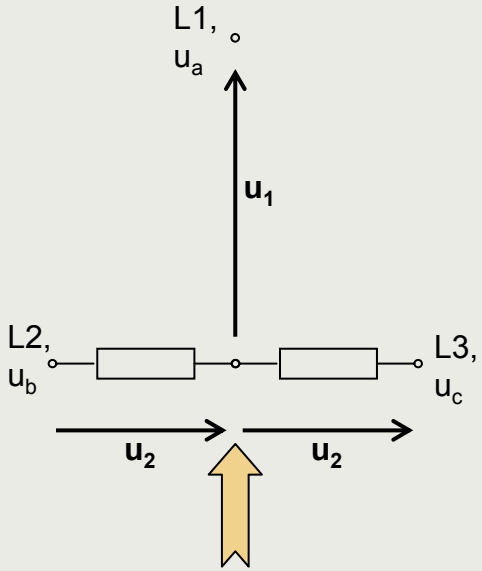
## *Asynchronous Direct On-Line (DOL) Switch-On*

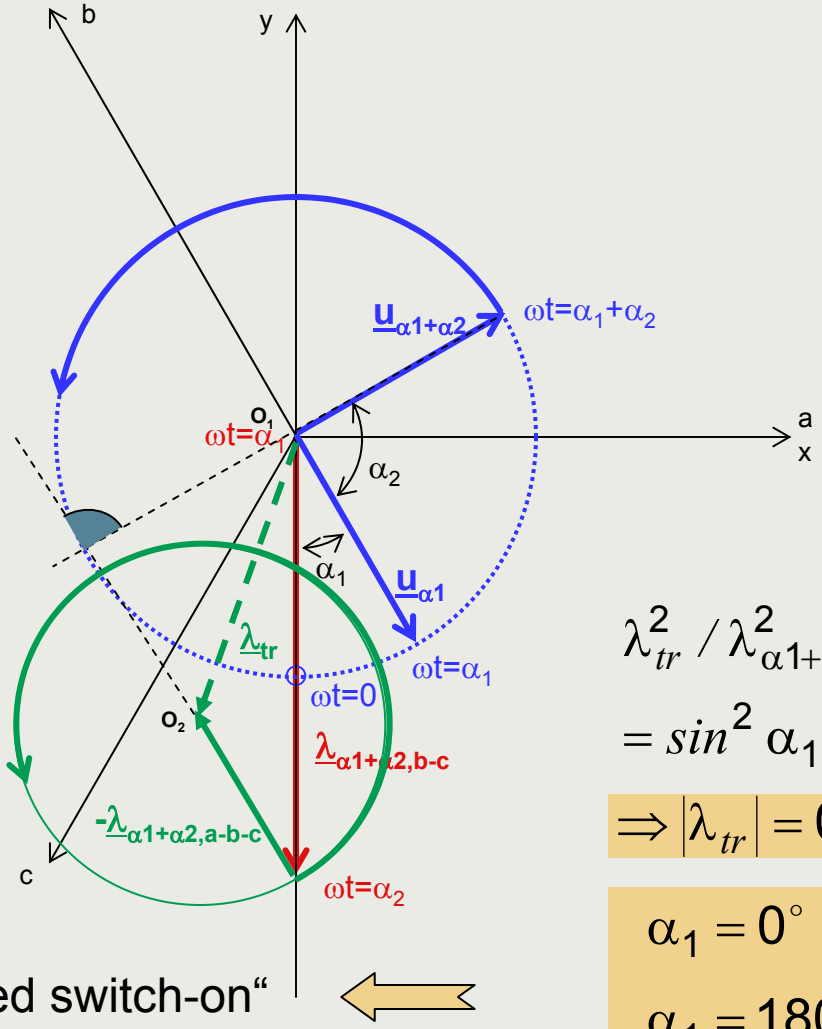
- Transient voltage and flux linkage phasor trajectories due to 2/3-phase asynchronous switch-on



- Transient voltage and flux linkage phasor trajectories due to 2-3-phase asynchronous switch-on




„zero crossing + 90° shifted switch-on“

$$\lambda_{tr}^2 / \lambda_{\alpha 1+\alpha 2,a-b-c}^2 =$$

$$= sin^2\,\alpha_1 + cos^2(\alpha_1+\alpha_2)$$

$$\Rightarrow |\lambda_{tr}| = 0 \quad if$$

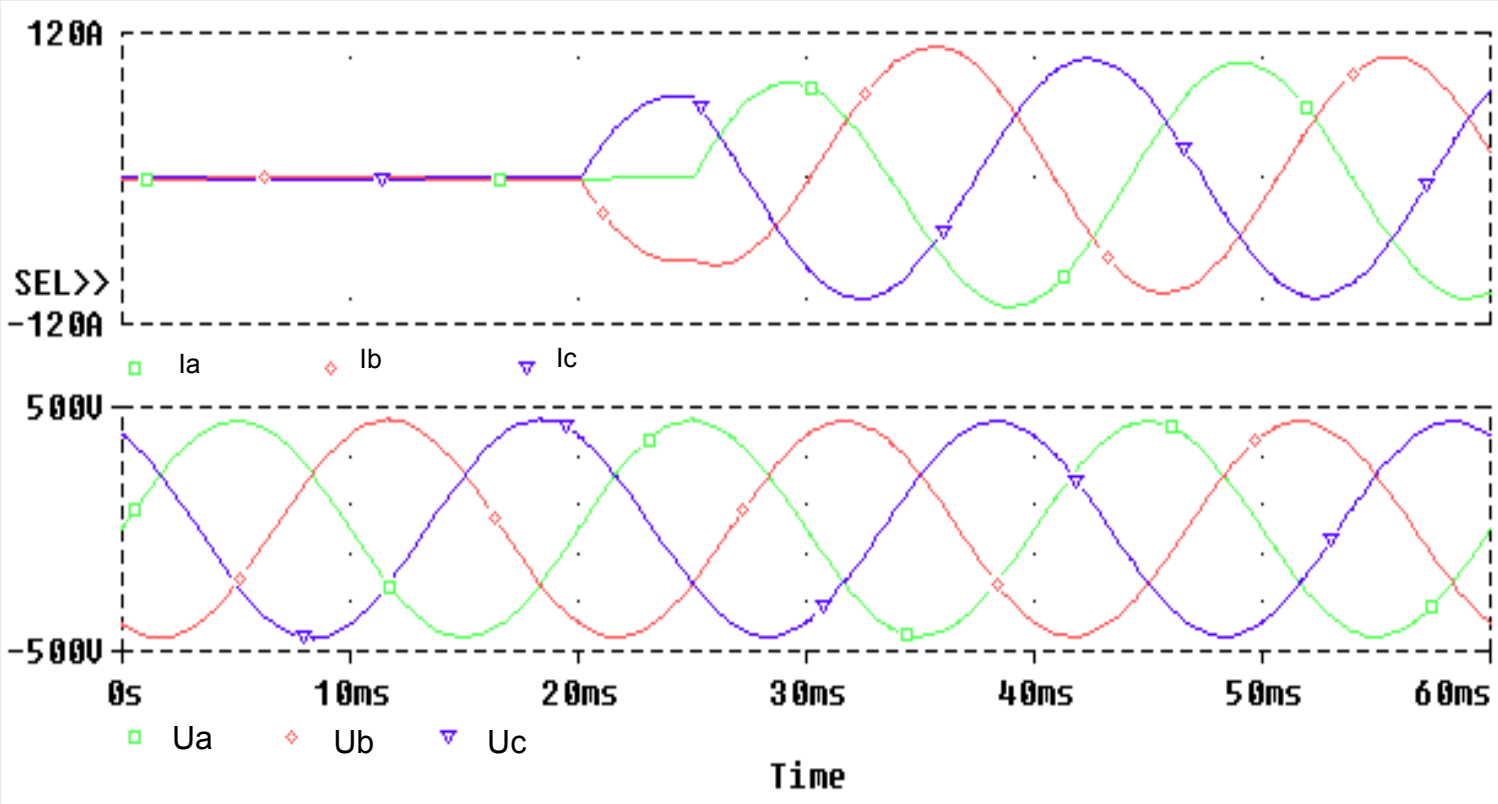
$$\alpha_1 = 0^\circ \qquad \alpha_2 = 90^\circ$$

$$\alpha_1 = 180^\circ \qquad \alpha_2 = 90^\circ$$

# *Advanced Control of Soft Starters for Industrial Drives*

## *Asynchronous DOL Switch-On*

- Currents and voltages versus time at asynchronous switch-on



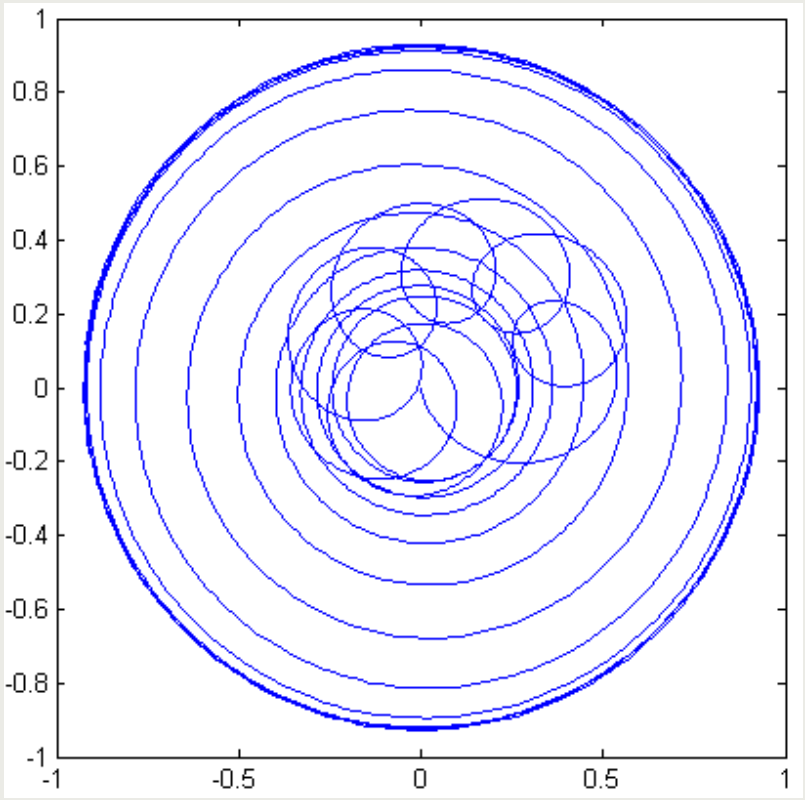
# *Advanced Control of Soft Starters for Industrial Drives*

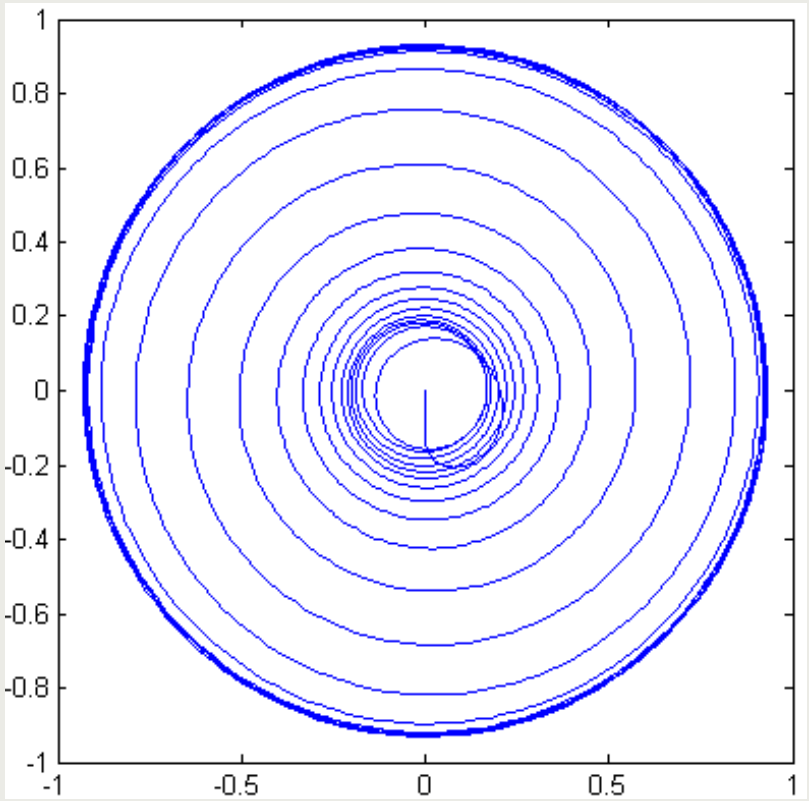
## *Comparison of synchronous and asynchronous DOL switch-on*

- Rotor flux linkage trajectories of an ASM during starting
  - in synchronous (l) and asynchronous (r) switching mode of operation

page 21

Start Simulink

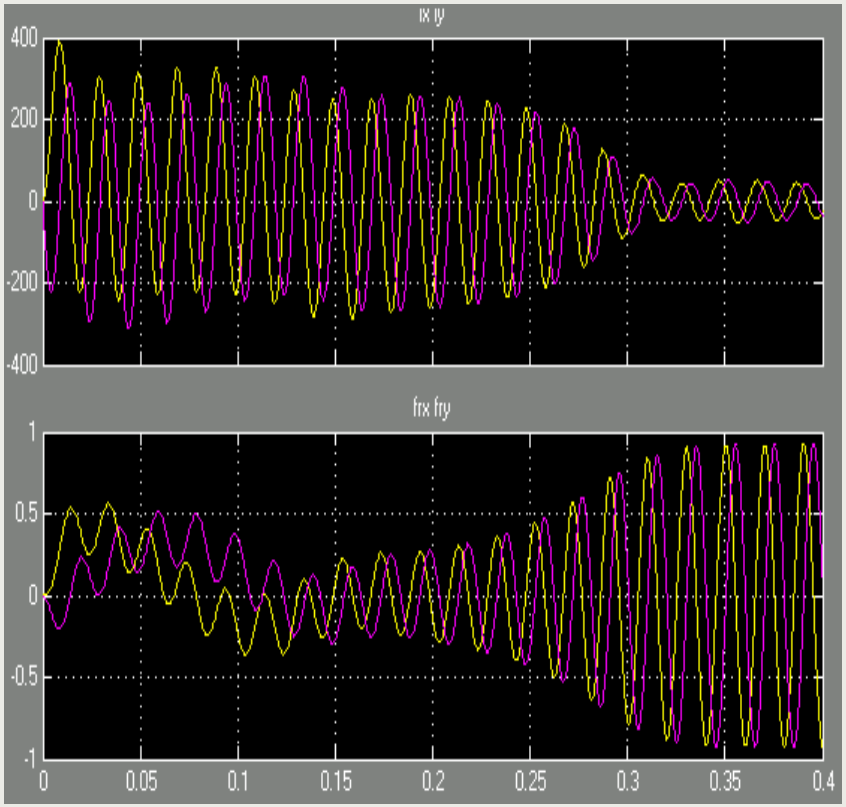


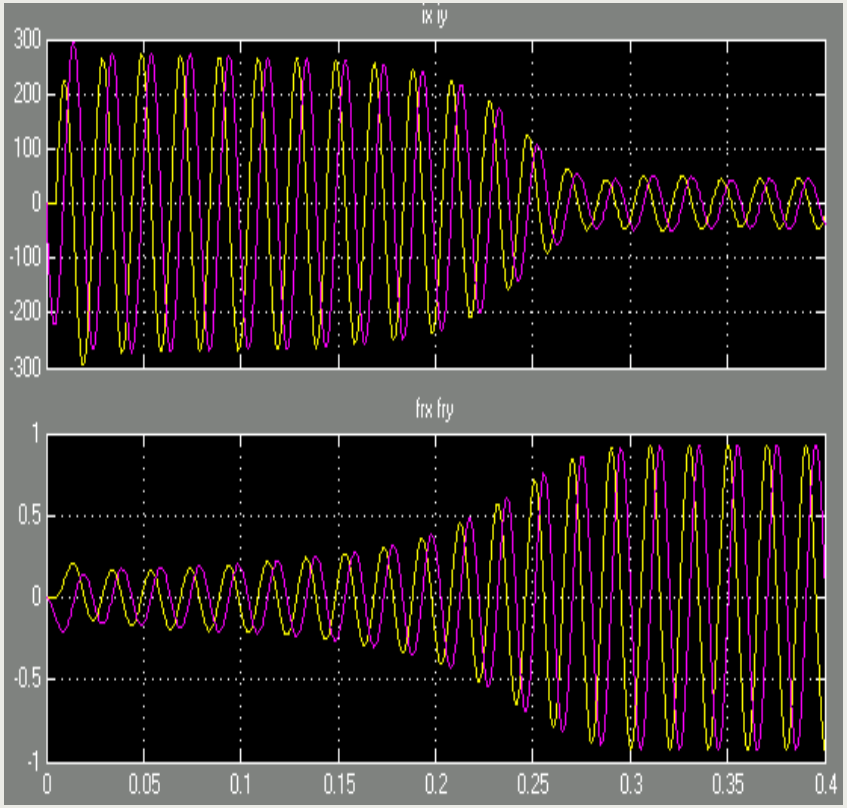



# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

- Rotor flux linkage and stator current versus time
  - in synchronous (l) and asynchronous (r) switching mode of operation

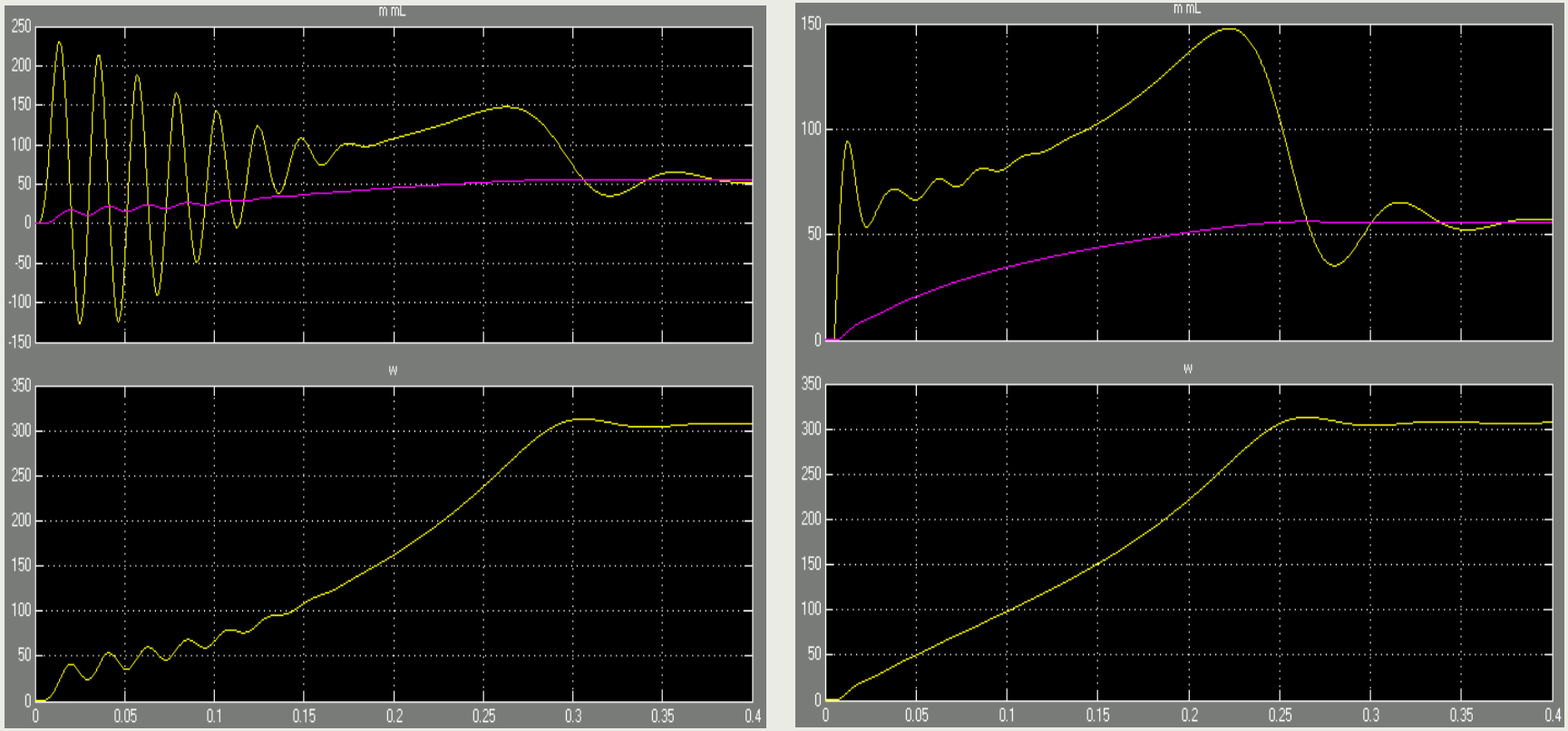


# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

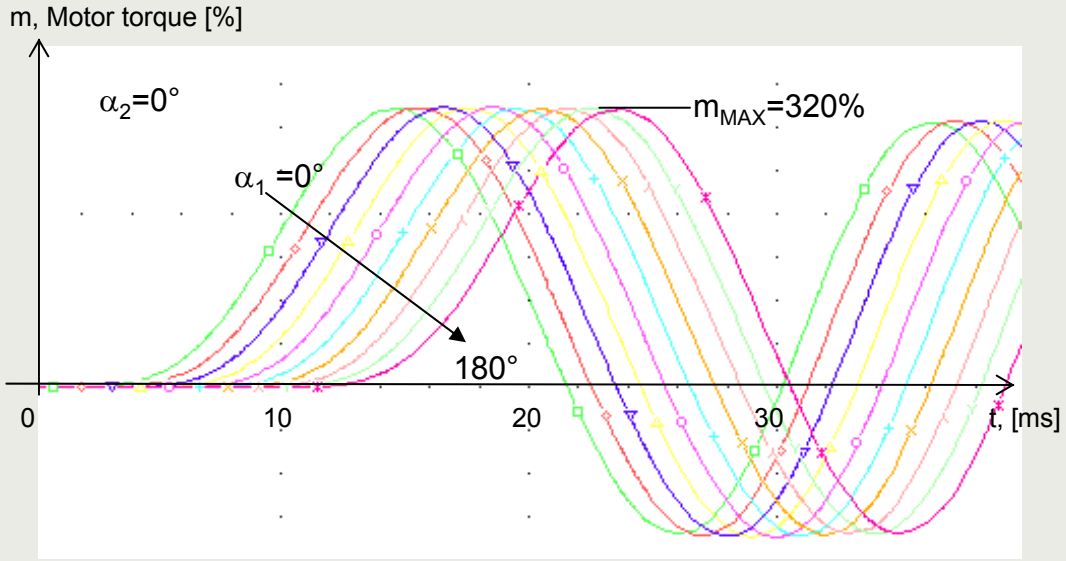
- Dynamic performance (torque and speed versus time)
  - in synchronous (l) and asynchronous (r) switching mode of operation



# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

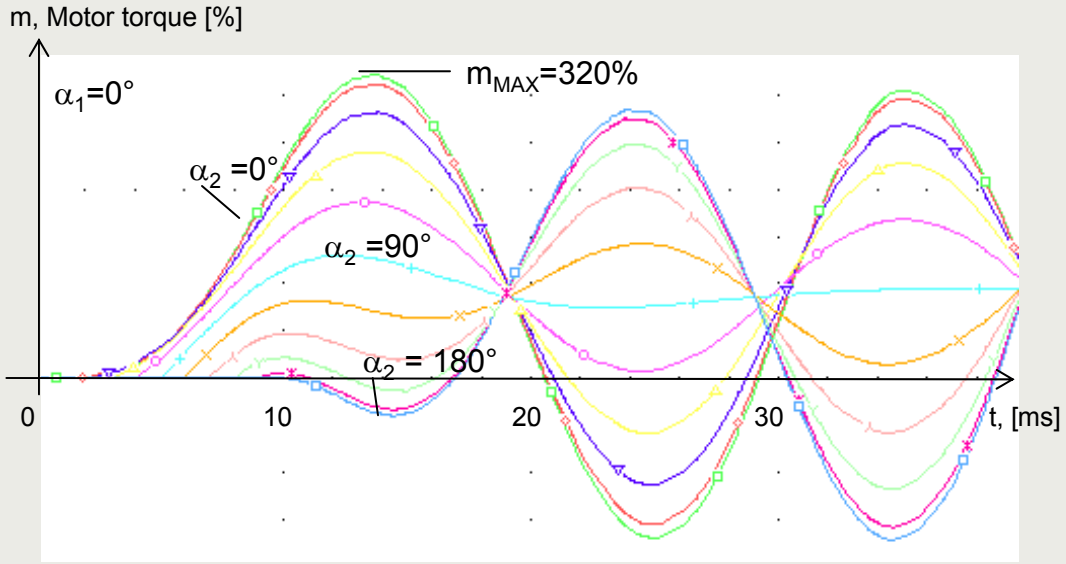
- Torque versus time
  - in synchronous switching mode of operation („switching in-phase“)



# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

- Torque versus time
  - in different asynchronous switching mode of operations
    - (1) various switching delay from the zero-crossing of the phase voltage




$$\lambda_{tr}^2 / \lambda_{\alpha 1+\alpha 2,a-b-c}^2 =$$

$$= sin^2 \alpha_1 + cos^2(\alpha_1 + \alpha_2)$$

$$\Rightarrow |\lambda_{tr}| = 0 \quad if$$

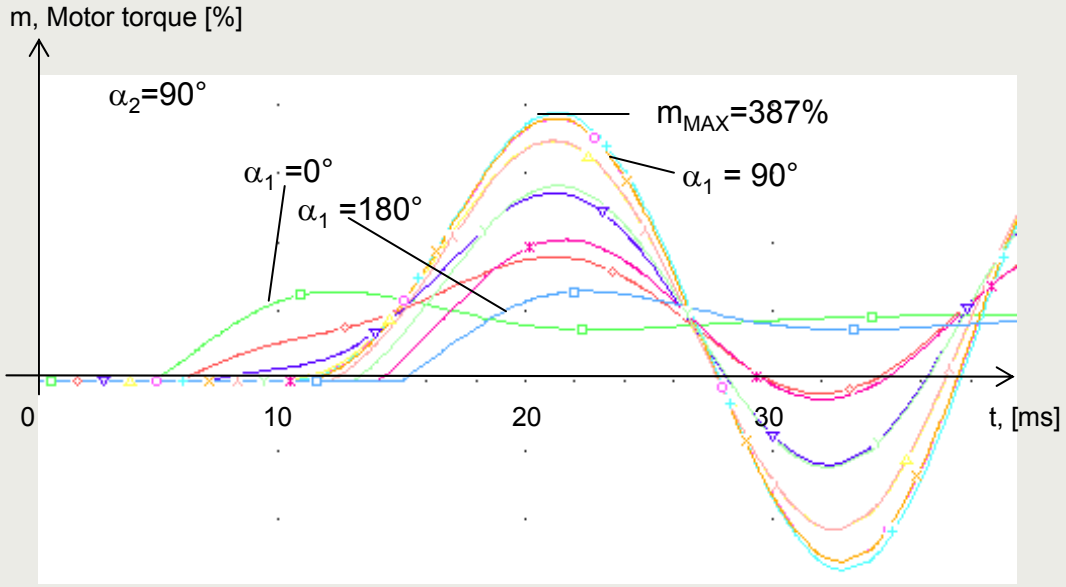
$$\alpha_1 = 0^\circ \qquad \alpha_2 = 90^\circ$$

$$\alpha_1 = 180^\circ \qquad \alpha_2 = 90^\circ$$

# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

- Torque versus time
  - in different asynchronous switching mode of operations
    - (2) various phase / 90° delay : two optimal switching processes exist




$$\lambda_{tr}^2 / \lambda_{\alpha 1+\alpha 2,a-b-c}^2 =$$

$$= sin^2 \alpha_1 + cos^2(\alpha_1 + \alpha_2)$$

$$\Rightarrow |\lambda_{tr}| = 0 \quad if$$

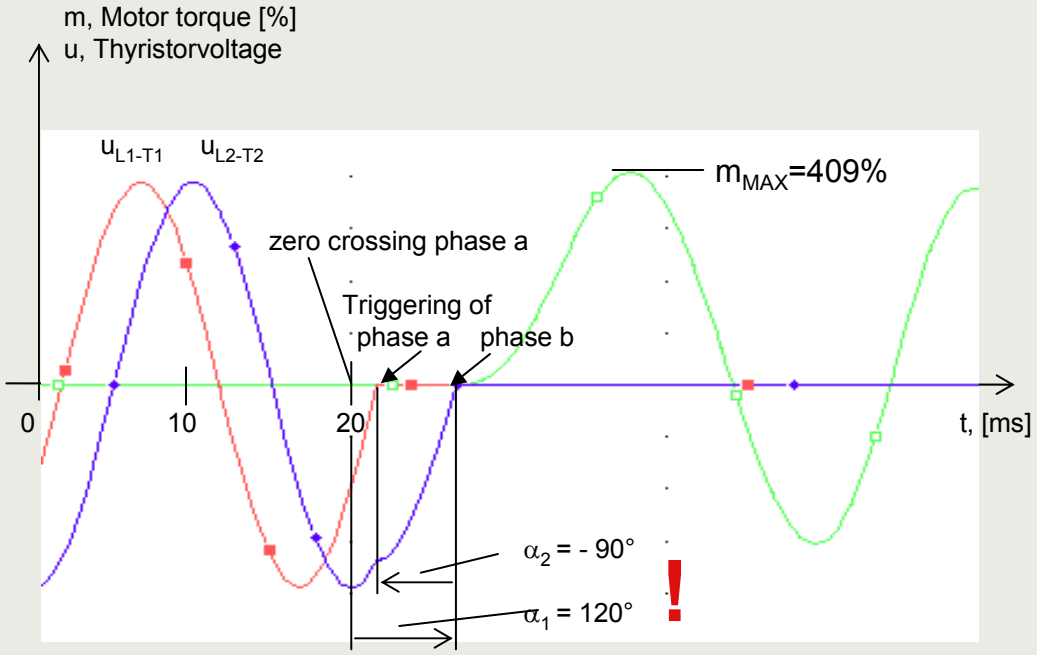
$$\alpha_1 = 0^\circ \qquad \alpha_2 = 90^\circ$$

$$\alpha_1 = 180^\circ \qquad \alpha_2 = 90^\circ$$

# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

- Torque versus time
  - in different asynchronous switching mode of operations
    - (3) switching in the zero-crossing point of the thyristor voltages




$$\lambda_{tr}^2 / \lambda_{\alpha 1+\alpha 2,a-b-c}^2 =$$

$$= sin^2 \alpha_1 + cos^2(\alpha_1 + \alpha_2)$$

$$\Rightarrow |\lambda_{tr}| = 0 \quad if$$

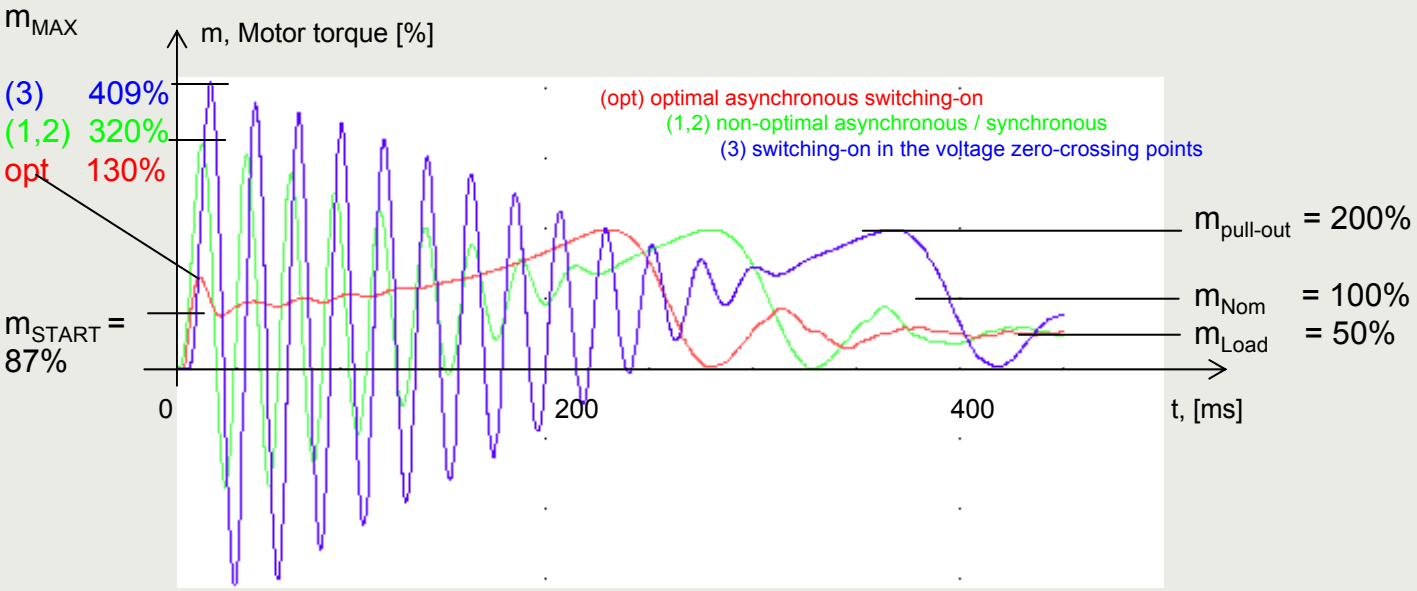
$$\alpha_1 = 0^\circ \qquad \alpha_2 = 90^\circ$$

$$\alpha_1 = 180^\circ \qquad \alpha_2 = 90^\circ$$

# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

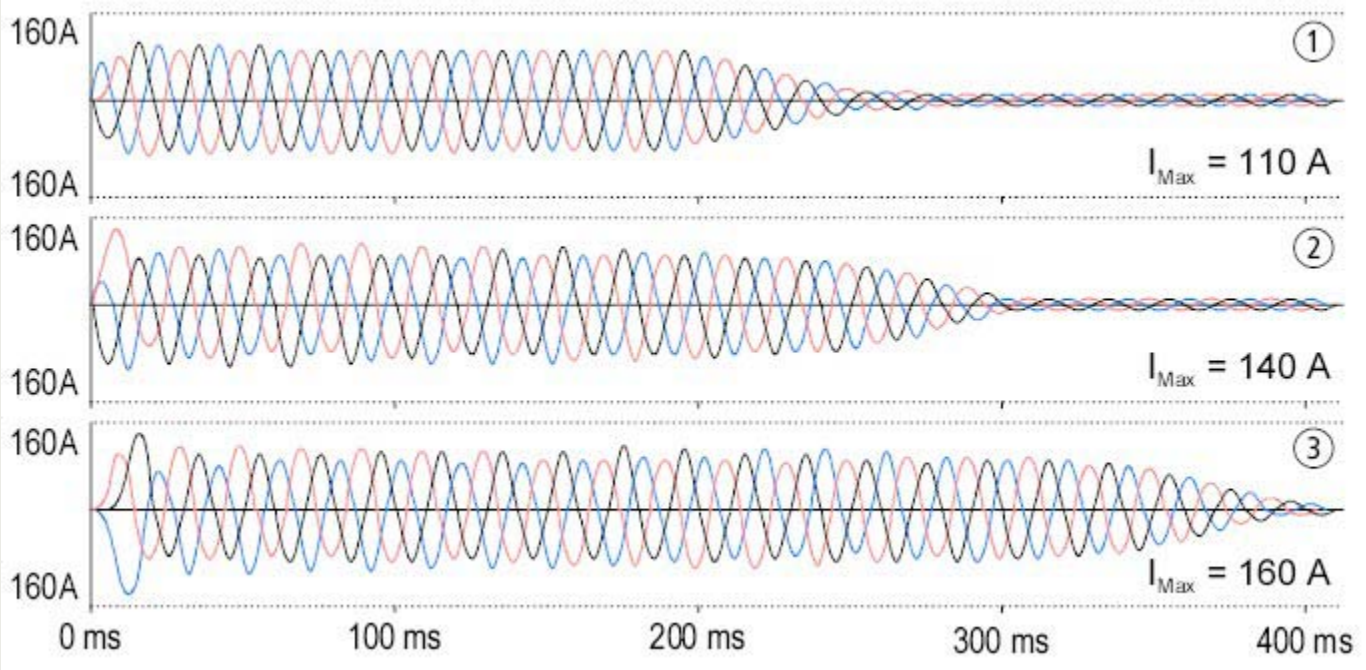
- Dynamic performance (torque versus time, 11 kW ASM)
  - in different synchronous and asynchronous switching mode of operations
    - switching in the zero-crossing points of the thyristor voltages (3): worst-case



# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

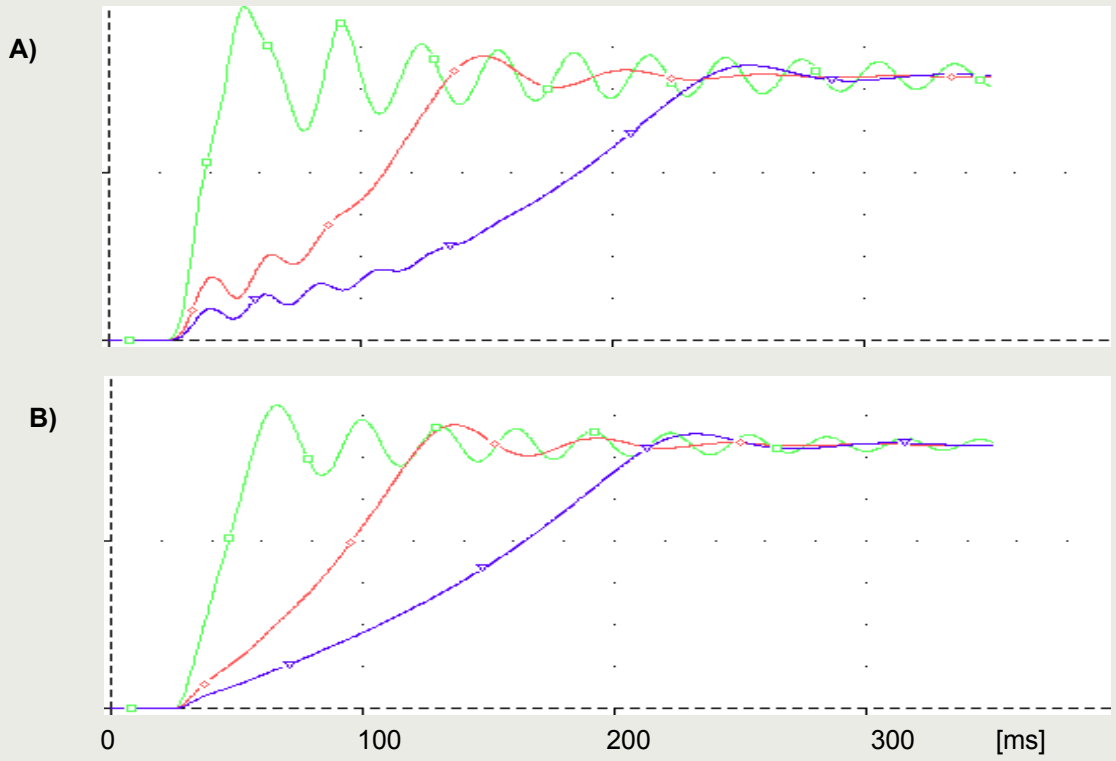
- Line currents versus time (11 kW ASM)
  - in different synchronous and asynchronous switching mode of operations
    - (1) optimal asynchronous switching: best case
    - (2) synchronous switching in-phase
    - (3) switching in the zero-crossing points of the thyristor voltages: worst-case



# *Advanced Control of Soft Starters for Industrial Drives*

## *Comparison of synchronous and asynchronous DOL switch-on*

- Dynamic performance (speed versus time) of an 0.75 kW ASM with various load in synchronous and asynchronous switching mode of operations
  - (A) in phase, (B) optimal asynchronous



- Benefits
  - Electrical
    - Reduced starting current
    - Reduced oscillating starting torque (motor winding friendly operation)
    - Reduced voltage dropouts of the net at starting
    - Nominal power increasing by bypass contacts
    - Same technology and structure at wide range of power (0,5kW.....15MW)
    - Wide range of voltage (3x110V.....3x6kV)
    - Robust solid-state devices
    - High switching frequency
  - Mechanical
    - Reduced starting shocks
      - No displacing or dropping goods on conveyor belts
      - Stress reduction on couplings and other transmission devices (conveyor belt, cone belt, clutch and driving elements)
      - No hydraulic shocks, Pump water hammer avoiding
      - Intelligent control of pumping systems

- Benefits
  - Electrical
  - Mechanical
  - Economical
    - Eliminates electro-mechanical starters and the maintenance required for these devices
    - Extended life of motor and mechanical parts
    - Reduced maintenance, downtime, parts and repairs
    - Smaller dimensions and mass
    - Electrical wiring simplification (3 wires in 3 wires out)
    - Easy handling and adjustment
    - Digital and software based control

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)

ilge pumps, winches)

water, irrigation, oil, chemical, petrochemical,

(sc

ers

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical,

(screw, piston)

ers, P

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, in chemical, petrochemical, offshore applications)
  - Fans, Blowers, Air Compressors (screw, piston)

ers,

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers,
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, Stone (mills, conveyors, crushers)
  - Marine, Offshore (bow thruster, bilge pumps, winches)
  - Centrifugal Pumps (water, waste water, irrigation, oil, chemical, petrochemical, offshore)
  - Fans, Blowers, Air Compressors (screw, piston)

    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippers, Paper Refiners
  - Rotating Kilns
  - Saws and Planers
  - Ball Mills, Hammer Mills
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

    * Escalators
    * Airport Baggage Conveyors
    * Bottling Lines

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

- Main Applications
  - Building technology (air condition, electrical heating equipment, light control)
  - Traffic light control
  - Mining, Opencast mining, Cement, s)
  - Marine, Offshore (bow thruster, bil
  - Centrifugal Pumps (water, waste w ochemical, offshore)
  - Fans, Blowers, Air Compressors (s
    Mixers, Areators, Centrifuges
  - Crushers, Grinders, Wood Chippe
  - Rotating Kilns
  - Saws and Planers, Mills
  - Mass product appliances
  - Load Transportation
    - Conveyors, Belts, Chains
    - Roller Tables
    - Monorails

# *Advanced Control of Soft Starters for Industrial Drives*

## *Soft starter application examples*

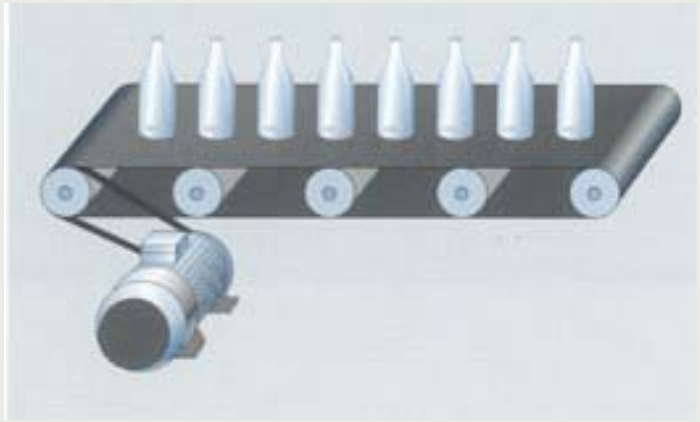
- Main Applications

- Load Transportation
  - Conveyors, Belts, Chains
  - Roller Tables
  - Monorails

* Escalators
* Airport Baggage Conveyors
* Bottling Lines

# *Advanced Control of Soft Starters for Industrial Drives*

## *Summary - Motto*



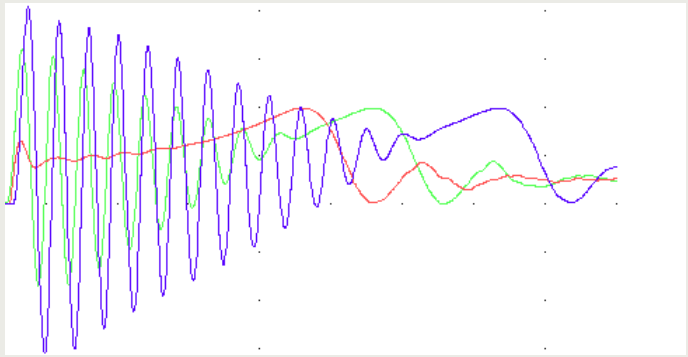
Practical Problem

+

=

„**There is nothing as practical as a good theory**“

**Boltzman**



Theoretical Solution

***Thank you for your attention***

***Questions are welcome***