Integrated Synchronous Motor Protection and Control

Pero Ostojic, GE Digital Energy
Chris Stinson, Air Liquide

INTRODUCTION

Key Synchronous Motor Features

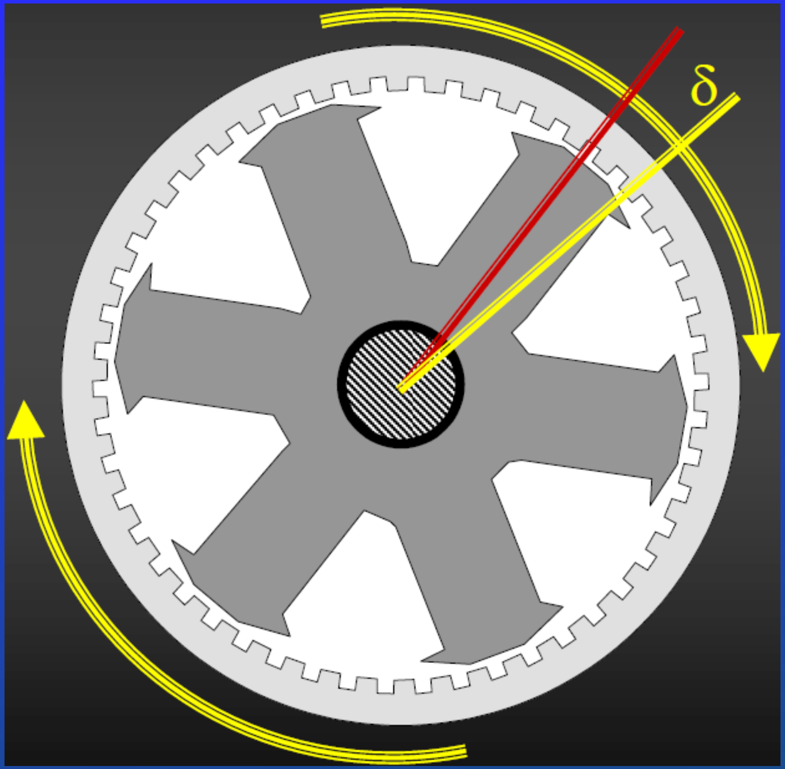
- Fixed rotational speed
- Adjustable power factor
- High efficiency
- Suitable for VFD control
- Moderate starting torque
- Complex controls

SYNCHRONOUS MOTOR BASICS

Fixed rotational speed:

$$N = 120 \times f / p$$

N - Rotating speed in RPM (1200)
f - System frequency in Hz
p - Number of motor poles



Rotor Angle

Motor Torque:

$$T = Tm * \sin(\delta * p / 2)$$

T - Motor torque

Tm - Maximum motor torque

δ - Mechanical angle between rotor and stator fields

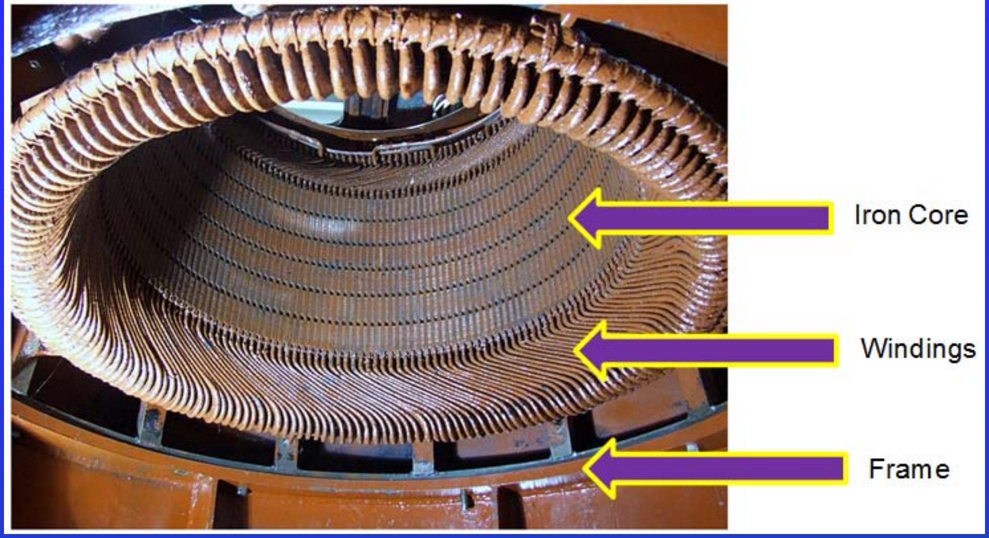
p - Number of motor poles

$0 < (\delta \times p / 2) < 90$

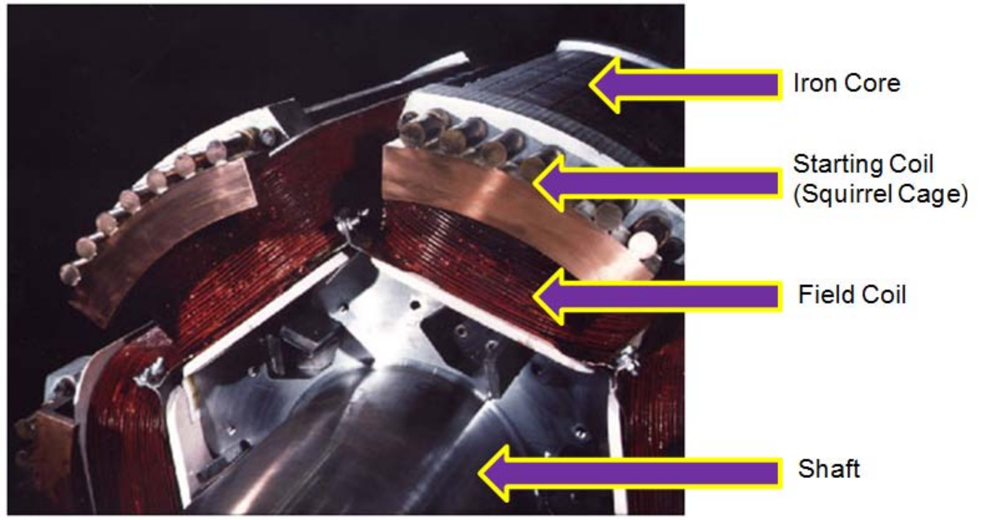
Design Options and Operational Modes

- Cylindrical Rotor
- Salient Pole Rotor
- Reluctance Motor
- PM Rotor
- Brushless Motor
- Slip Ring Motor

- Starting Mode. Starting coil creates ~ 40% torque.
- Synchronous Mode. Field coil is supplied with DC power.



Stator



Salient Pole Rotor

Comparison with Induction Motor

Characteristics	Induction	Synchronous
Efficiency	High	Very high
Power factor (Note [1)])	0.5-0.90 lagging	Possible to select (lagging - unity - leading)
Reactive power	Consumed	Note [2)]
Susceptibility to voltage dips	Low	Medium
Rotor		
Rotation speed	Slower than stator field, "slip"	Same speed as stator field, "synchronous"
Lead torque variation	Some speed variations due to load torque variations	Fixed speed, independent of load torque variations
Current in rotor	AC	DC
Magnetization	By induction	By exciter (fed from excitation panel)
Design	Laminated Squirrel cage or slip ring	Salient poles - Solid (high speed) or laminated (slow speed) Brushless
Starting (slip = 1.0 p.u.)		
Current	Higher	Lower
Torque	Lower	Higher

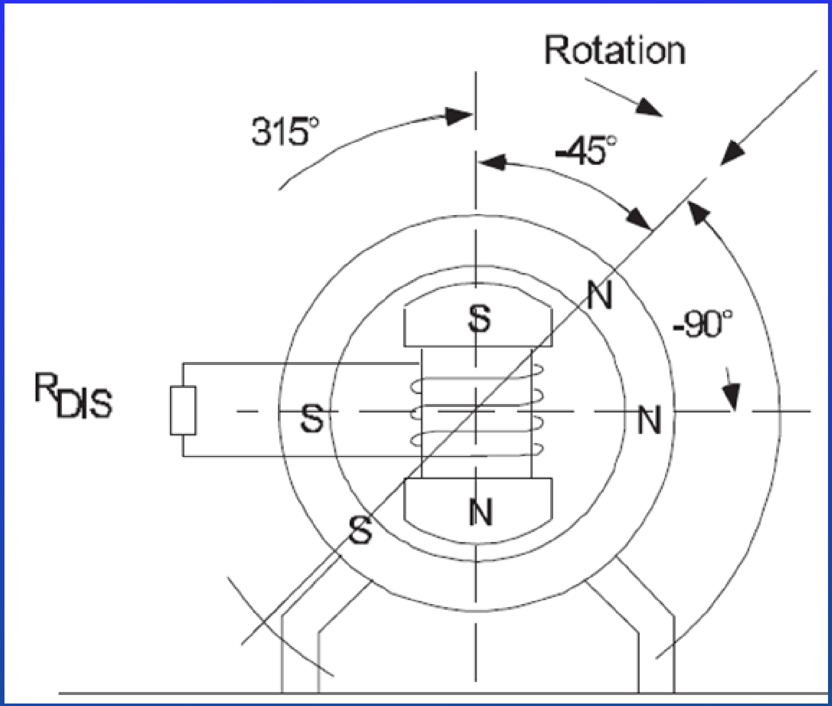
Notes:

[1)] Power factor
- the power factor for an induction is always lagging and is depending on pole-numbers, the higher the pole number, the lower the power factor
- the power factor for the synchronous is possible to design to "any value" but normally a power factor is selected in the range 1.0 - 0.8 leading, i.e. the motor produces reactive power to the net. A synchronous motor very seldom runs lagging.

[2)] Reactive power
- Lagging power factor: consumed
- Unity power factor: motor is neither consuming nor producing
- Leading power factor: produced

KEY CONTROL FUNCTIONS
Starting Sequence

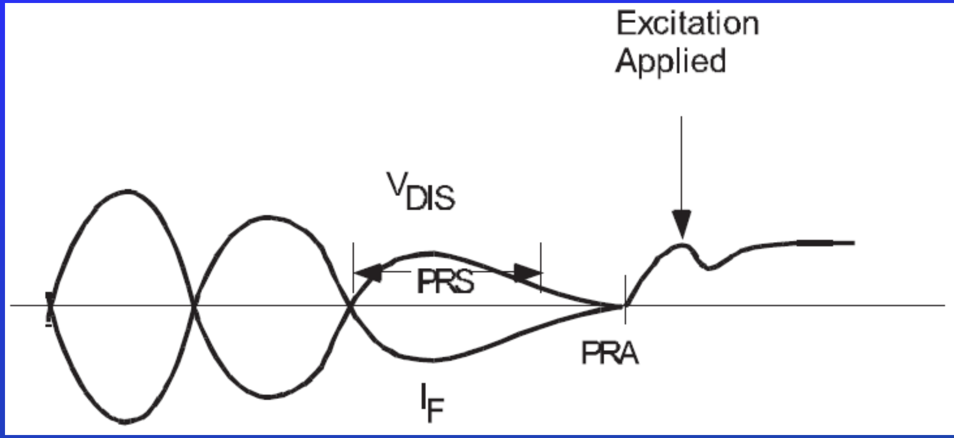
- Applying power to the stator
- Shunting the field with a discharge resistor
- Sensing rotor speed
- Sensing rotor angle
- Applying excitation at optimum speed and angle



Discharging Resistor Connection

Starting Sequence (continued)

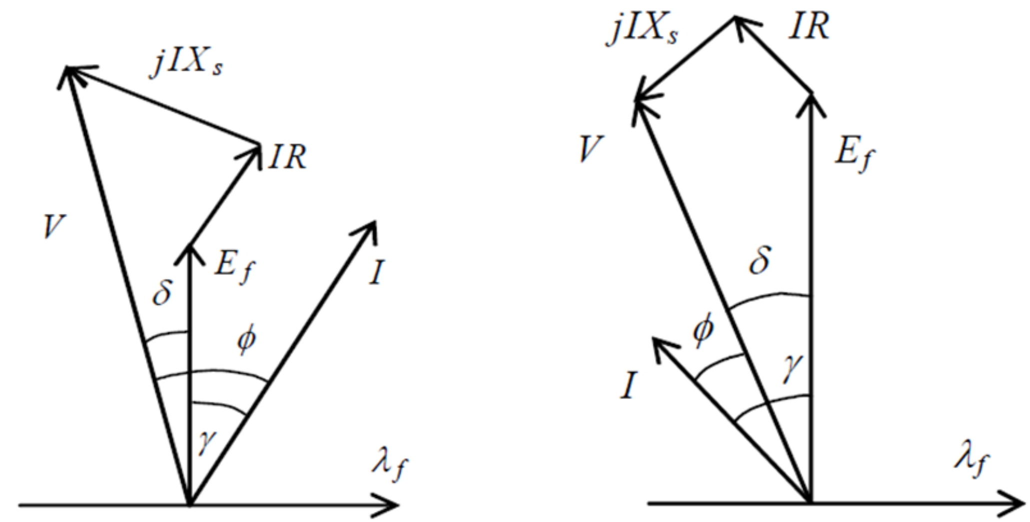
- The discharging resistor current and voltage are used to determine the speed and the position of the rotor.
- Zero crossings of the field current and voltage is monitored.
- Pull in typically happens when the rotor reaches about 95% of the synchronous speed.
- The command has to be issued before the perfect position occurs, to compensate for the response time of the switching device.



Typical Synchronization Graph

VDIS	- Voltage Across Discharging Resistor
IF	- Field Coil Current
PRS	- Field Power Application Delay
PRA	- Proper Rotor Angle

Power Factor

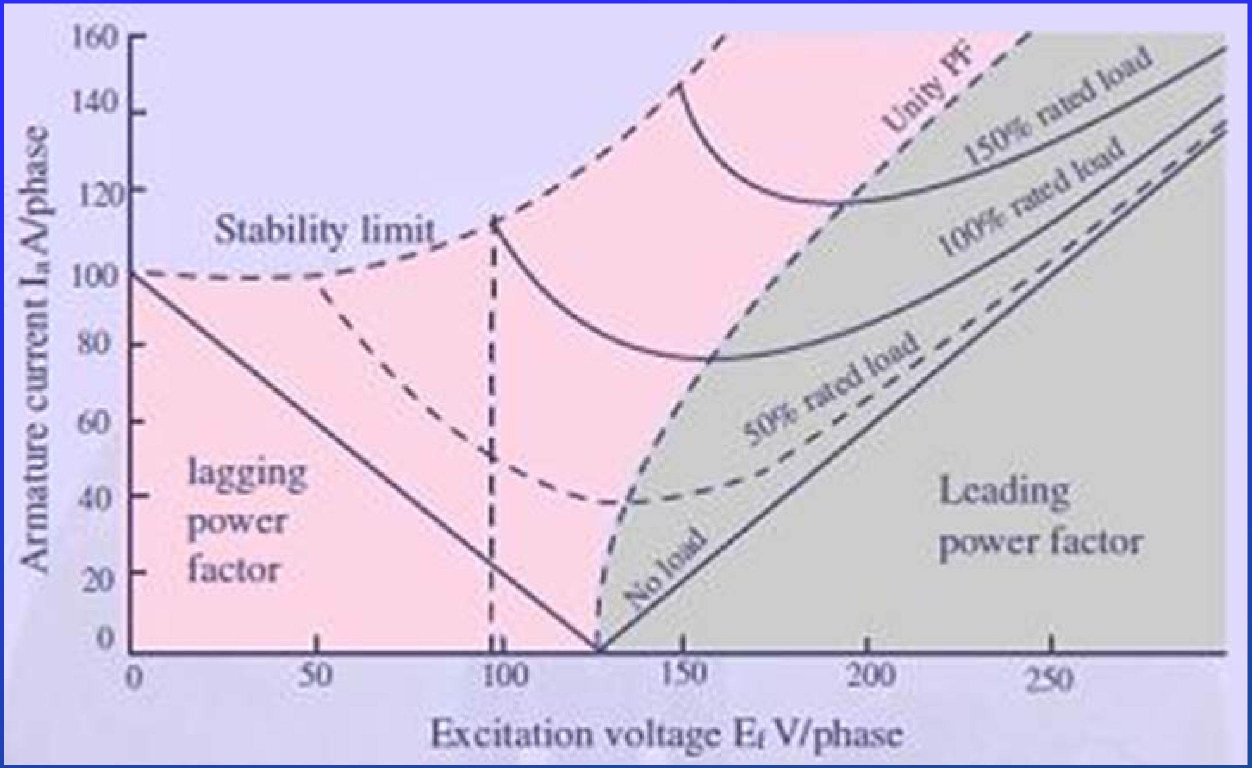


(a) Underexcited motor (b) Overexcited motor

V - Phase voltage
E_f - Motor electromotive force
I - Phase current
R - Stator resistance
X_s - Stator reactance
ϕ - Power factor angle
δ - Rotor angle
λ_f - Direction of the rotor field

The power factor is controlled by regulating the field current. A lower field current will decrease the magnitude of the motor's electromotive force, which has to be balanced with the external voltage applied to the motor. The motor is said to be under-excited and this will cause the power factor to become more lagging. If the field current is increased, the power factor will become more leading.

Stability Limits



V Curve of a Synchronous Motor

- The motor is becoming unstable when the field current drops below certain level.
- Under-excited condition occurs only in the lagging region.

TYPICAL PROTECTION ELEMENTS

STATOR WINDINGS PROTECTION:

- Thermal overload protection
- Pole slip protection
- Locked rotor protection
- Repeat starts protection
- Overcurrent protection
- Undercurrent protection
- Negative sequence current protection
- Single phasing protection
- Differential protection
- Phase reversal protection
- Ground fault protection
- Under voltage protection
- Over voltage protection
- Under frequency protection
- Over frequency protection

ROTOR FIELD COIL PROTECTION:

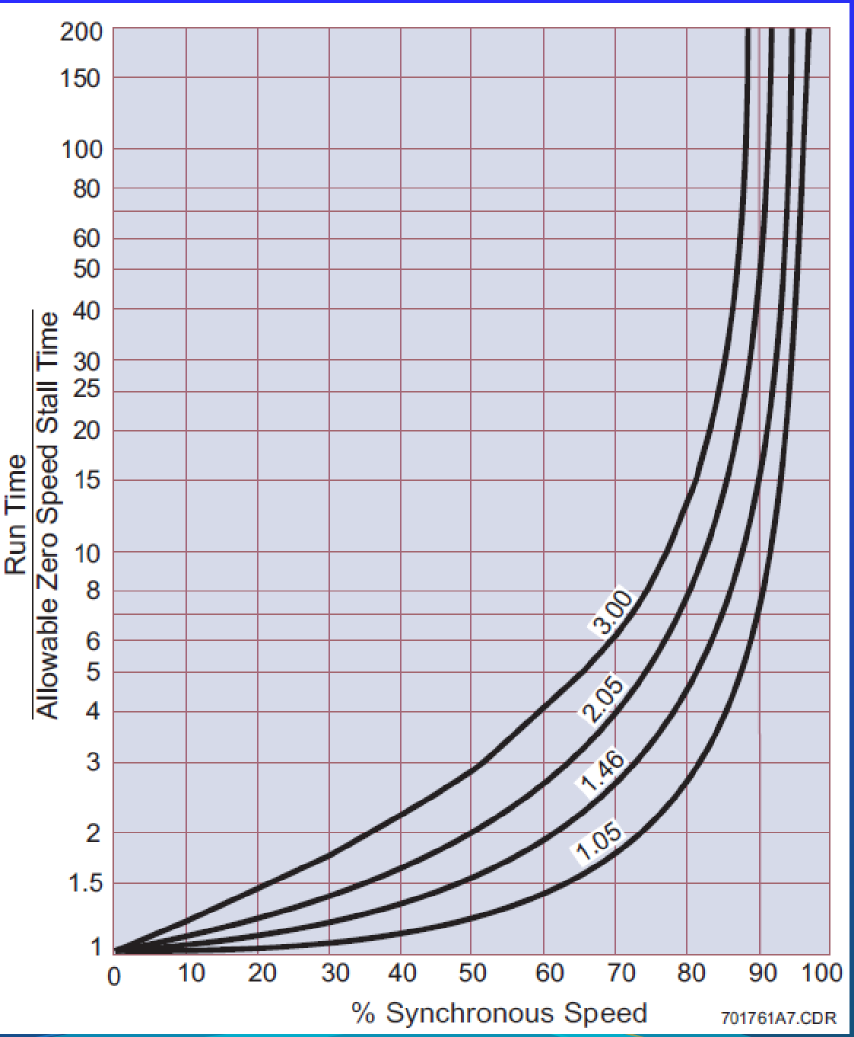
- Undercurrent protection
- Overcurrent protection
- Under voltage protection
- Over voltage protection
- Ground fault protection

ROTOR STARTING CAGE PROTECTION:

- Stall time protection
- Start time protection

Rotor Starting Cage Protection

- The rotor starting cage of a synchronous motor is the element most vulnerable to thermal damage. An important protective function of the relay is to prevent overheating of the cage winding both during starting and running out of synchronism.
- Motor designers always place a limit on the time a motor can be allowed to remain stalled ("allowable stall time"). An accelerated schedule can then be established for the motor in terms of running time at any speed less than synchronous as a percent of allowable stall time. Designer's curves for speed versus time can be used for protection by software that integrates the time-speed function.
- The curve label (1.05 to 3.00) is the time that the motor may run at 50% speed and is expressed as a multiple of the allowable motor stall time.



Starting Cage Protection Curves

Pole Slip Protection

Pole slip can occur with the field poles magnetized while running in synchronism from the following four major causes:

1. A gradual increase in load beyond the pull-out capabilities of the motor.
2. A slow decrease in field current.
3. A sudden large impact load.
4. A power system fault or voltage dip lasting long enough to cause pull-out.

One of the most reliable indicators of asynchronous (out-of-step) operation is the motor power factor. Lagging power factor appears when the motor load angle increases beyond rated, becoming almost fully lagging (90°) as the motor slips out-of-step.

Rotor Field Coil Protection

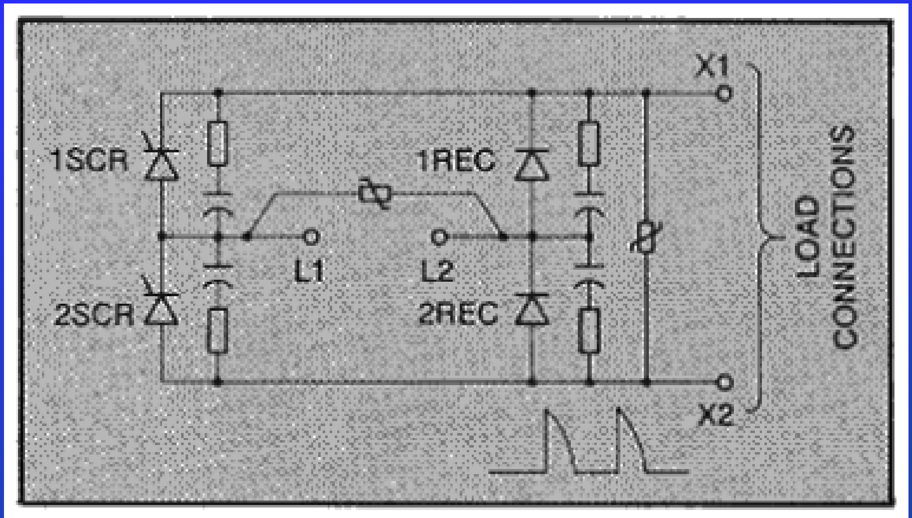
- Rotor voltage, current and temperature are monitored to detect abnormal conditions.
- The most important segment of the protection is the undercurrent protection since the undercurrent condition may result in a loss of synchronism. If the current drops below the minimum threshold, the motor should trip.
- In general, a trip condition will disconnect the main breaker but the DC power supply should never be disconnected before the main breaker has tripped.
- The field overcurrent condition is also not desired and it usually sets up an alarm.

Stator Windings Protection

- A standard profile of the actual values being monitored by the protection relay is: phase currents, phase voltages and winding temperatures. The hardware components required are:
    - 3 phase current transformers,
    - 3 differential current transformers,
    - 1 ground transformer,
    - 3 phase voltage transformers
    - 6 temperature probes (RTDs).
- The most important and the most complex part of the stator protection is thermal protection, which is based on the motor thermal model.
- The other protection elements usually used are: ground fault, negative sequence current, differential current, negative sequence voltage, undervoltage and overvoltage.

SUPPORTING DEVICES
DC Power Supply

- It is typically a controlled three phase rectifier
- On some smaller motors a single phase input is used.
- The reference for this circuit typically comes from an analog DC voltage or current input.



Single Phase DC Power Supply

Microprocessor Units

- The key microprocessor unit for synchronous motor operation is the field current regulator. This regulator typically runs a PID (Proportional, Integral, and Derivative) algorithm processing several inputs and feeding an analog DC output. That output is connected to the DC power supply. In some cases, the regulator is integrated into the power unit. Protection of the field coil is usually integrated into the field current regulator.
- The second microprocessor unit is a protection relay. Most of the protection relays available on the market today are designed to protect induction motors. They can protect the stator of a synchronous motor. Some models have a power factor element suitable for synchronous motor protection. Protection of the starting cage is also provided.
- The third microprocessor unit is a standard PLC (Programmable Logic Controller). It is typically used as a master logic controller. PLCs are usually equipped with an external HMI (Human Machine Interface).

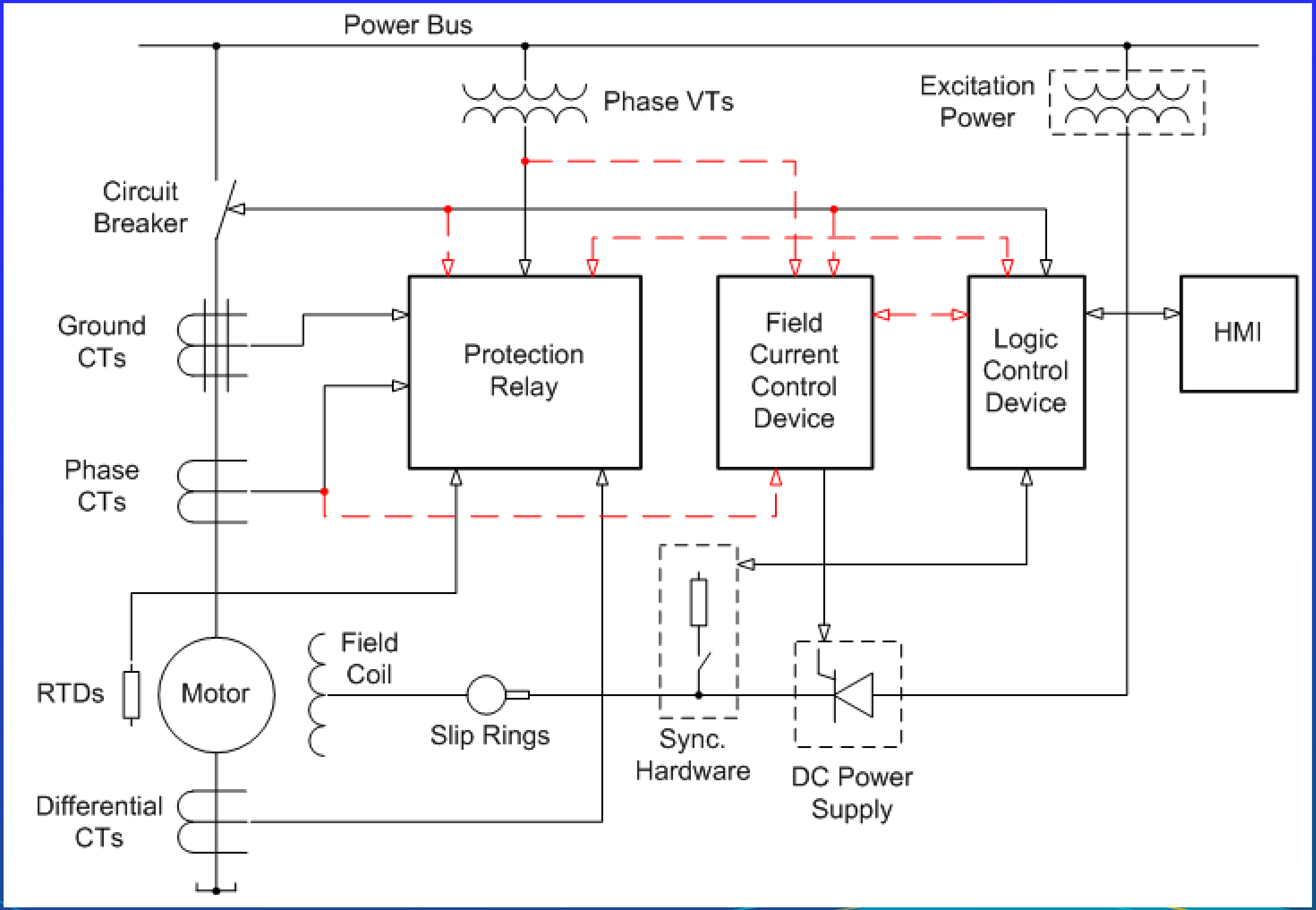
Layout Options

- The distribution of functional blocks, protection elements and commands to the three microprocessor units can vary from case to case. For example, most PLCs today have a PID algorithm as a standard built in function block and that makes them suitable to work as field current regulators.
- Integration of different electronic devices is an easy task for today’s technology. A typical input / output (I/O) hardware configuration of this unit should include:

7 CT inputs (3 phase currents, 3 differential currents, 1 ground current)
3 VT inputs (phase voltages)
2 analog DC inputs (field current and field voltage)
1 analog DC output (field current reference)

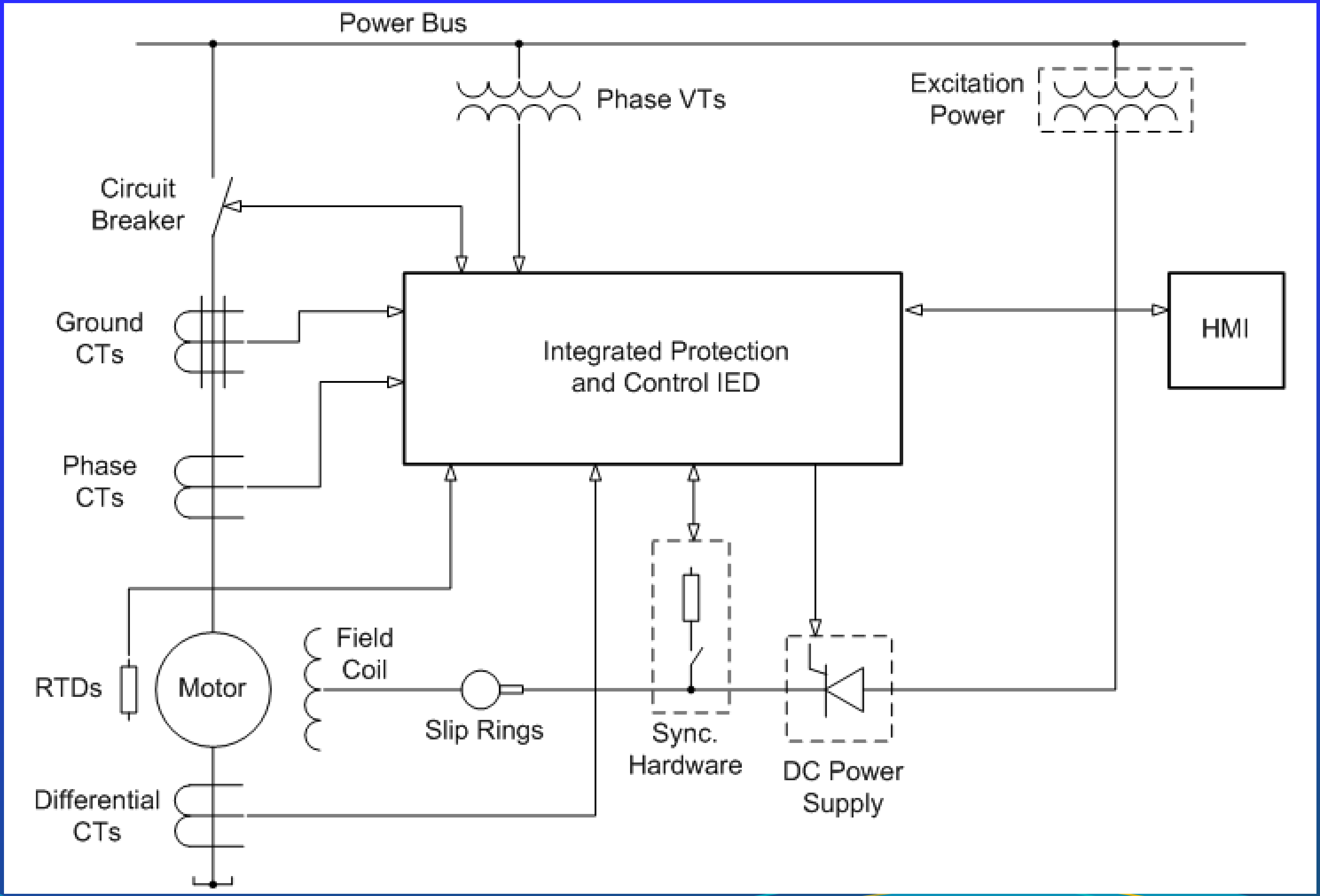
- This device could be modular and have all the above connection points placed on I/O modules that could be inserted (or removed) to corresponding slots. Another possibility is to have a compact unit with all the above points fixed on its backplane. The faceplate is usually equipped with a simple display and a couple of pushbuttons to execute basic commands. A feature that should also be included is a capability to connect to a PC and run special software that would allow the user to set up and control the unit remotely.

Layout Options (continued)



Distributed Layout

Layout Options (continued)



Integrated Layout

Layout Options (continued)

Technical aspects of integration of synchronous motor protection and control:

- Inputs and outputs (I/O): In distributed layout, each microprocessor unit used for this application has its own set of I/O modules These inputs and outputs can be of different type, voltage level, sensitivity, etc. This requires the usage of additional components, more wiring and results in lower reliability compared to the integrated layout
- Communication: Multiple microprocessor units need to communicate to each other and exchange relevant information. This routine takes away a part of the processing power and creates a slight time delay. In addition, the communication system is usually susceptible to noise.
- Maintenance: The advantages of the integrated layout from the maintenance perspective are: reduced number of spare parts and a unique diagnostic system.
- Simplicity: In the integrated unit, the number of the key hardware components (CPU, power supply, front panel display etc.) is reduced to one third compared to the distributed layout. The integrated layout has fewer connections, which means less wiring and a smaller amount of information to be exchanged. Furthermore, on the distributed layout, each IED has its own procedures, protocols and syntax rules. Dealing with all these complicated procedures creates a serious obstacle for the user. An additional problem will arise if the system consists of multiple electronic devices produced by different manufacturers.

CONCLUSIONS

- Designing protection and control systems for synchronous motors is a challenging task. Equally demanding is to define a proper setup for each application.
- Synchronous motor protection and control systems are very advanced today but can still be improved further.
- The proposed integration of the protection and control system is an attempt to find a simpler and more reliable solution.

The End

THANK YOU!

QUESTIONS?