Automation concept for an electrically excited synchronous motor: Setup and requirements specification
Automaatiokonsepti vierasmagnetoidulle tahtimoottorille: Laitteisto ja vaatimusmäärittely

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Kandidaatintyö
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Tarkastaja: Tero Ahonen

Tämä kandinaatintyö kuuluu osaksi Lappeenrannan yliopistossa kesällä 2011 tehtyyn tutkimusprojektiin. Projektin tavoitteena oli luoda automaatiokonsepti vierasmagnetoidun tahtimoottorin ohjausta varten. Tämä työ keskittyy konseptin laitteisto- ja vaatimusmäärittely osaan.

Tahtikonekäyttö sisältää ABB AC500 PLC isäntälaitteen, DCS800 magnetointilaitteen ja ACS800-taajuusmuuttajan. ACS800 taajuusmuuttaja käyttää kestomagneettimoottori ohjelmistoa ohjaamaan staattorin magneettikenttää, tasavirtakäyttö ohjaa moottorin magnetointia, ja AC500 PLC-isäntä hallitsee laitteiston kommunikointia ja toiminnallisuutta. Vaatimusmäärittely esittelee lyhyesti konseptin yleiskuvan, ohjelmoitavan logiikan ohjelman toimintamallin sekä koko konseptille että ohjelmalle liittyvät toiminnallisuusehdot, jotta ne toimisivat annettujen vaatimusten mukaisesti.

ABSTRACT

Lappeenranta University of Technology
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Automation concept for an electrically excited synchronous motor: Setup and requirements specification
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Bachelor's Thesis.
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This bachelor's thesis is a part of the research project realized in the summer 2011 in Lappeenranta University of Technology. The goal of the project was to create an automation concept for controlling an electrically excited synchronous motor. This thesis concentrates on the setup and requirements specification part of the concept.

The setup consists of ABB AC500 as the PLC master device, DCS800 as an exciter and ACS800 as a frequency converter. The ACS800 frequency converter uses permanent magnet synchronous machine software to control the stator's magnetic field, the DC drive handles the excitation and the AC500 PLC master controls the communication and functionality of the system. The requirements specification briefly explains the general overview of the concept, the use and functionality of the PLC program and the requirements needed for the whole concept and the PLC program to work as intended.

CONTENTS

ABBREVIATIONS AND ACRONYMS

AC31	Advant Controller 31 control system module made by ABB
AC500	Type of PLC made by ABB
ACS800	Frequency Converter type made by ABB
ACT	Actual Value
CM572	Communication Module of AC50
CP-E 24/2.5	24 V 2.5 A Power supply made by ABB
CPU	Central Processing Unit
CW	Command Word
DC505	Field plug bus module made by ABB
DCF506	Overvoltage Protection Unit made by ABB
DP	Decentral Periphery
DTC	Direct Torque Control
EMC	Electromagnetic Compatibility
FPB	Flash Protection Boundary
I/O	Input / Output
LV	Low Voltage
PI	Proportional Integral (controller)
PKW	Parameter Identification Value (Parameter-Kennung-Wert)
PLC	Programmable Logic Controller
PM Sw	Permanent Magnet Software
PM583	PLC made by ABB
PPO	Parameter Process data Object
PWM	Pulse-width Modulation
PZD	Process Data (Prozessdaten)
REF	Reference Value
RPBA	R-series Profibus adapter module made by ABB
RS	Requirements Specification
S500	Circuit Breaker made by ABB
SW	Status Word
VSI	Voltage-source Inverter
$\cos \varphi$	Power factor

INTRODUCTION

This thesis describes the initial setup, requirements specification, installation and configuration of a low voltage (LV) synchronous motor automation concept. The goal was to create an externally excited synchronous machine setup composing a frequency converter, an external exciter and a PLC controlling the system. The frequency converter uses permanent magnet synchronous machine software while the DC drive handles the excitation, and the programmable logic controller (PLC) controls the communication and functionality of the system.

1. SETUP

In this project, we had ABB AC500 as the PLC master device, DCS800 as an external exciter, also known as a field exciter, and ACS800 as a frequency converter. Using these devices, we had to create a working setup to run the externally excited synchronous motor. This consisted of making necessary preparations for planning the setup, making appropriate PLC program and testing the final system thoroughly.

The setup has four main components: the synchronous motor, AC drive, DC drive and the PLC. This chapter describes the basic functionalities for each of these equipment and the communication protocol used between the devices.

1.1 Synchronous motor

Synchronous motor is an AC motor whose rotor follows the stator’s rotating magnetic field at the synchronous speed which is determined by the number of pairs of poles and the mains supply frequency.

The transverse armature field created by the active stator current and the main field created by the excitation current produce the torque needed to keep up the motor’s rotational speed. (Aura & Tonteri, 1986)

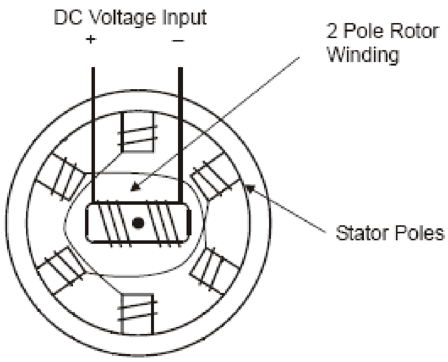

Figure 1.1 A simplified internal structure for 2 pole synchronous motor. (Pyrhönen, 2006)

1.1.1 Excitation

For synchronous machine's excitation both the armature winding and the field winding need to be excited. The field winding, or rather the pole winding, is excited with the help of the slip ring in the brushless exciter motors.

When using the slip ring, the rotational speed of the motor doesn't have an effect on the overall operation of the system and the voltage in the pole winding can be easily and almost instantly controlled and changed from a positive value to negative value and vice versa. (Niiranen, 2000)

1.1.2 Start up

In this project, the synchronous motor is handled like a permanent-magnet motor. It is controlled with AC and DC drives. The DC drive first generates the excitation current needed to make a permanent-magnet-like rotating magnetic field in the stator. Then, the AC drive produces a controllable current that controls the actual operation of the system by managing the armature field that is following the rotating stator magnetic field.

The rotating rotor speed *s* follows the equation

$$s = \frac{120 * f}{n}, \tag{1.1}$$

where *f* is the excitation current's frequency and *n* is the number of poles per phase.

With 3-phase, 4-pole synchronous motor this means that the motor will rotate at a maximum speed of *s* = 1500 rpm (rounds per minute) when the excitation current's frequency *f* is 50 Hz, that is the usual main supply frequency in Europe. (Basler Electric, 2003)

1.2 AC and DC drives

There are two types of frequency converters for the AC and DC motors: Direct frequency cycloconverters and frequency converters with intermediate circuits. We will be concentrating on the VSI (voltage source inverter) because the ABB ACS800 frequency converter, which is used in this project, uses VSI.

A voltage source inverter (VSI) has a diode bridge to produce the rectified voltage needed in the intermediate circuit. The diode bridge rectifies and prevents the braking power pushing back to the mains supply. A brake chopper is usually also needed in the intermediate circuit when the motor is needed to brake and when it has to dissipate electrical energy. The simplified structure of VSI can be seen in Figure 1.2.

As the functionality of the frequency inverter's power switch doesn't depend on the power factor of the load, the frequency inverters can be used with both the synchronous motors and the induction motors. (Niiranen, 2000)

The simplified operating principle of ACS800 drive can be summarized like this: ACS800 has four main functional components which are the rectifier, intermediate circuit, inverter and the control circuit. The supply AC voltage is rectified into a pulsating DC voltage in the drive's rectifier. This DC voltage is filtered through capacitors in the intermediate circuit, which also evens out the energy reservoir during commuting. Lastly, the inverter modifies the filtered voltage and its frequency into a desired AC voltage, which is then fed to the motor.

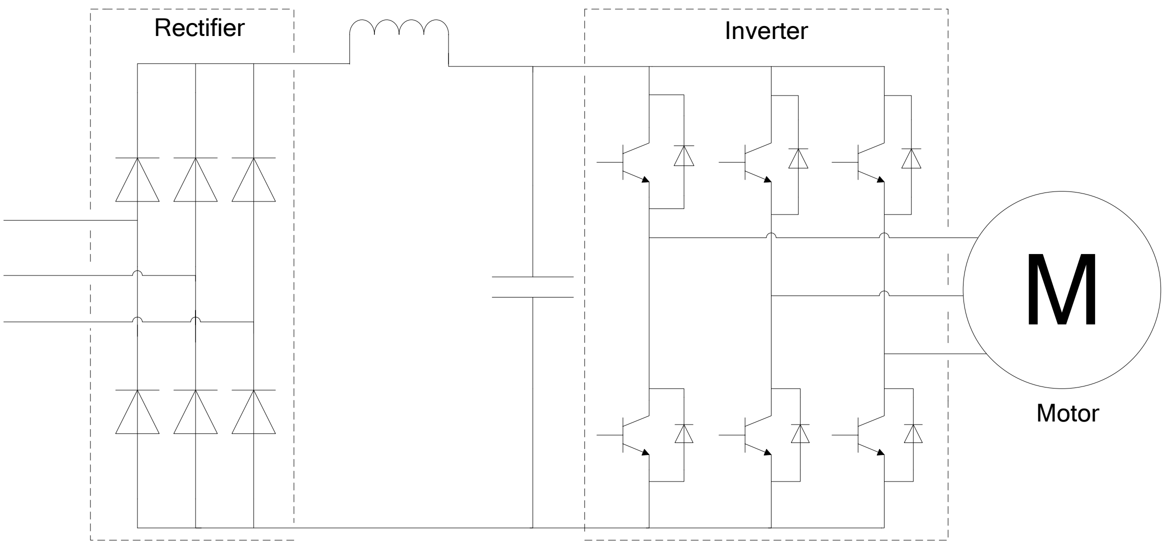

Figure 1.2 The circuit diagram of the VSI, voltage source inverter (Niiranen, 2000).

1.2.1 ACS800

Single drive configuration of an ABB ACS800 usually contains a DC link, rectifier and an inverter. The AC drive we use ACS800-01 has e.g. an EMC filter, line choke and a brake chopper. The communication can be handled using analogue and digital I/O extension modules or a Fieldbus module (ABB, 2012).

ACS800 uses e.g. Direct Torque Control technique which enables flux oriented control without any feedback. The controlled variables needed for this are the motor's magnetic flux and the torque. (Tuominen, 2010)

DTC is explained in more detail in (Niiranen, 2000) and in (ABB, 2011). Figure 1.3 is a simplified illustration of the DTC technique.

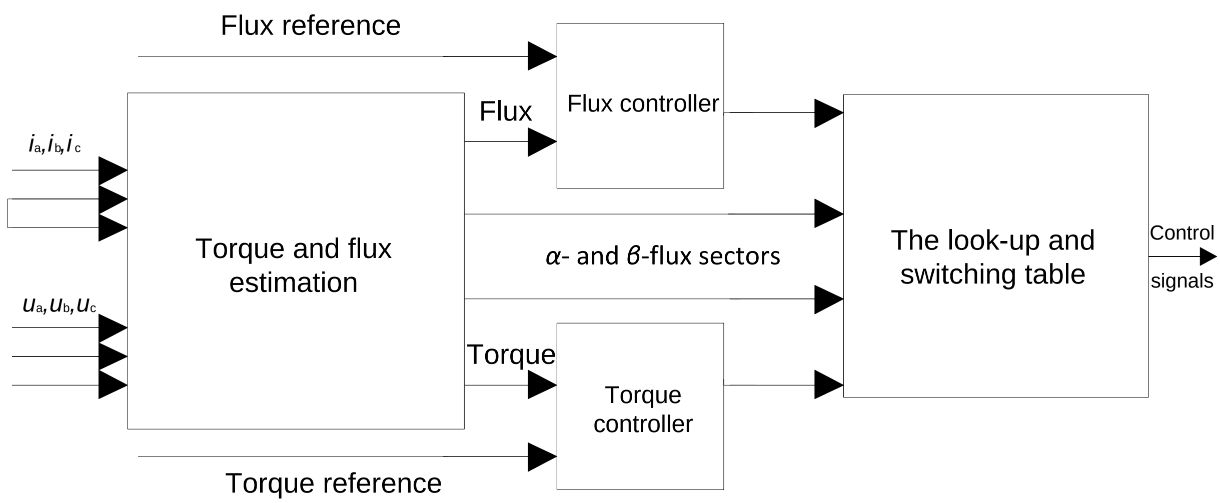

Figure 1.3 The simplified functionality block diagram of the DTC direct torque control (Niiranen, 2000), (ABB, 2011).

1.2.2 DCS800

In this project an ABB DCS800 converter (DCS800-S) is used to produce and control the field excitation current. It uses the same communication methods as ACS800 and in this project the main communication method used is Fielbus communication.

When used as a field exciter the DC drive usually needs a separate active overvoltage protection unit such as DCF506 for overvoltage protection. (ABB, 2008)

1.3 AC500 PLC

ABB AC500 is the main PLC used in this project. The basic electronic modules of the AC500 system are the central processing unit (CPU) and the couplers for various bus systems like: FPB PROFIBUS DP, CANopen, DeviceNet and Ethernet couplers. The AC500 principle system structure can be seen in Figure 1.4.

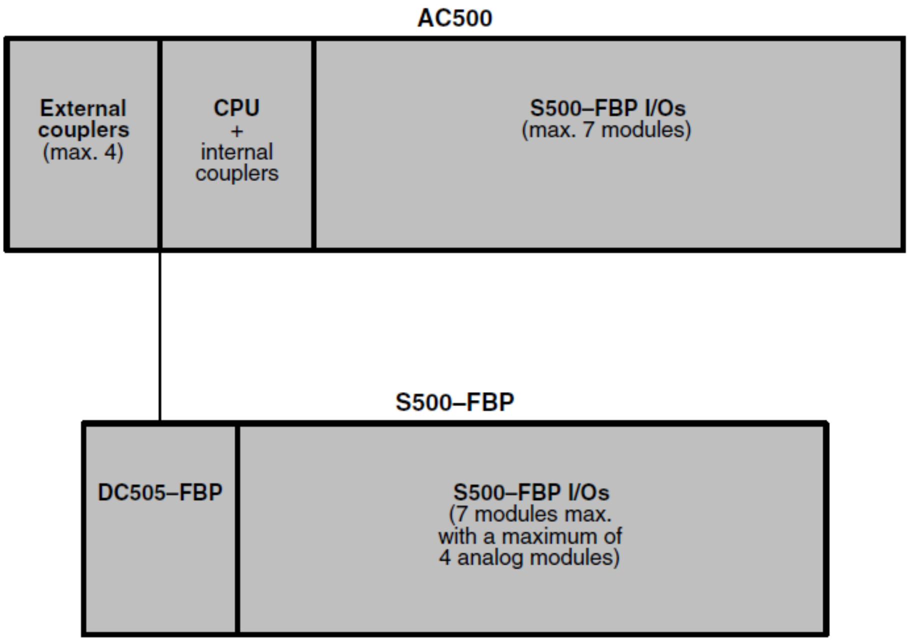

Figure 1.4 The system structure of AC500 PLC (ABB, 2007).

In the central expansion unit, a single CPU can support for up to seven directly connected S500 FPB system I/O devices. In the decentralized expansion unit, using the DC505 DP interface module, it is possible to connect up to seven more S500 FPB system I/O devices with a maximum of four analogue modules. (ABB, 2007)

In this project we use an AC500 system that has a PM583 CPU, CM572-DP coupler for Profibus communication and a CP-E 24/2.5 switch mode 24 voltage, 2.5 ampere power supply. The AC500 PLC system used in this project can be seen in Figure 1.5.

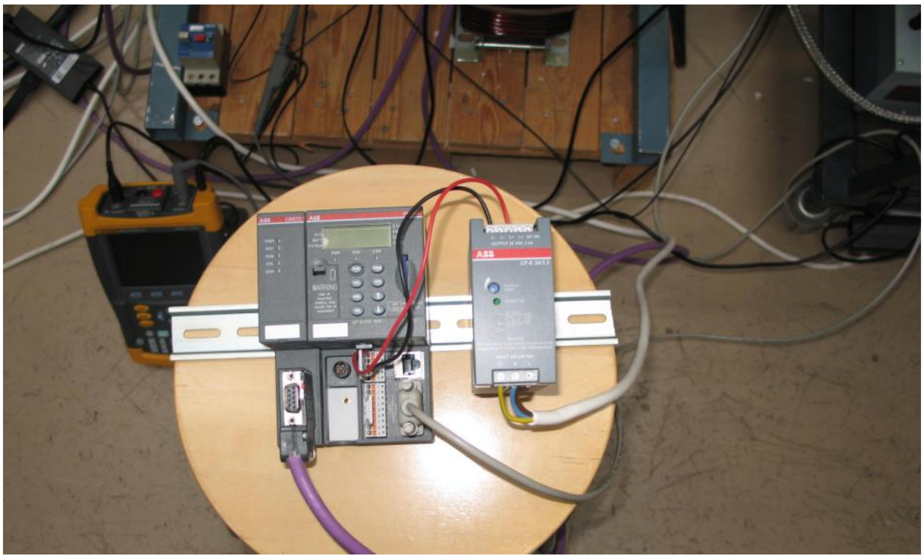

Figure 1.5 ABB AC500 PLC system with Profibus adapter and cable attached to it.

1.3.1 Profibus communication

Profibus DP (Process Field Bus - Decentral Periphery) bus systems can be used for both multi-master and master-slave communication in the field area. It can be used with AC500 and AC31 control system series and with the field bus neutral decentralized I/O intelligent switching devices the FBP devices. It can also be used with standard Profibus slave devices such as the communication adapter RPBA adapter module.

The communication is controlled through a master device. When the master has the bus access authorization token, it can transmit data without any external requests. Slave devices don't have any bus access rights, so they only acknowledge the received messages or respond to the queries that their master sends them. The Profibus can handle data transfer between a maximum of 126 devices.

The data is usually sent in cyclical mode between the master and the slave. The masters have full access to their assigned slaves, but a read-only access to the other masters' slaves. There is also an acyclical data exchange (DP-V1) mode, where the parameterization and diagnostics between the master and the slave can be done in parallel to the master's cyclical data traffic. In this project, we have one master device and two slave devices. (ABB, 2007)

2. REQUIREMENTS SPECIFICATION

There hasn't been much demand for low-voltage electrically excited synchronous motor drives before, which is why there is no readily available firmware for this kind of concept. However, the control of the synchronous motor drive can be realized with a PLC instead of the converter firmware changes. This chapter describes the requirement specification for such automation concept.

The requirements specification is formed in accordance with software requirements specification documentation (Juntunen & Lehtonen & Liljander, 2000).

2.1 Objectives

The main objective is to build a working synchronous motor automation concept. The system has a synchronous motor that is driven with an ACS800 frequency converter and the motor's excitation current is generated by a DCS800 DC drive. Both the AC and DC drives are controlled with an ABB AC500 PLC.

2.2 Outline of the RS

The basic outline of the requirements specification is divided into the following chapters:
Chapter 2.1 introduces reader to the subject and briefly describes the objectives of the study.
Chapter 2.3 describes the general overview of the concept explaining the use and the functionality of the devices, and how they work together forming the overall automation system.
Chapter 2.4 briefly presents all the functions that the system needs for working properly.
Chapter 2.5 explains the system's interfaces and used connections.
Chapter 2.6 goes through the rest of the features needed in the final concept.

2.3 Overview

The reference excitation current for the DCS800 exciter drive is calculated in the PLC. The PLC master AC500 communicates with the ACS800 and DCS800 slave devices transmitting the excitation reference current to the DCS800 and the speed or torque reference to the ACS800. The DCS800 then provides the excitation current to the synchronous motor's field winding, and the ACS800 provides the needed speed and torque realizing currents to the motor's armature winding.

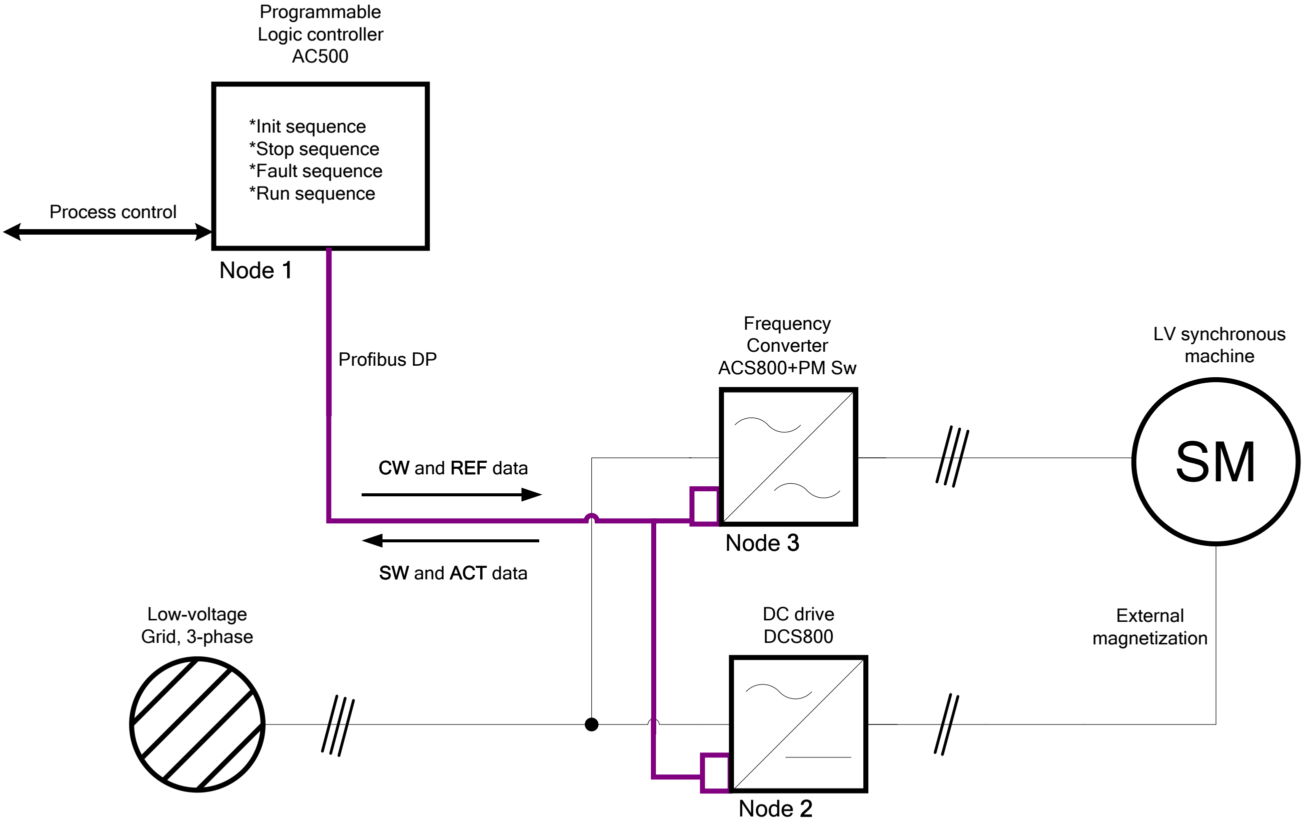

Figure 2.1 The overall structure of the synchronous motor automation concept. Profibus cable is highlighted with colour purple.

The system's automation is done with the AC500's PLC program. The excitation current for DCS800 is calculated from flux reference value, magnetizing level value etc. sent by the ACS800. In addition, the overall program has a state machine with four main states: "Start on Init", "Start", "Stop" and the "Fault" state. The general structure of the state machine is illustrated in Figure 2.2.

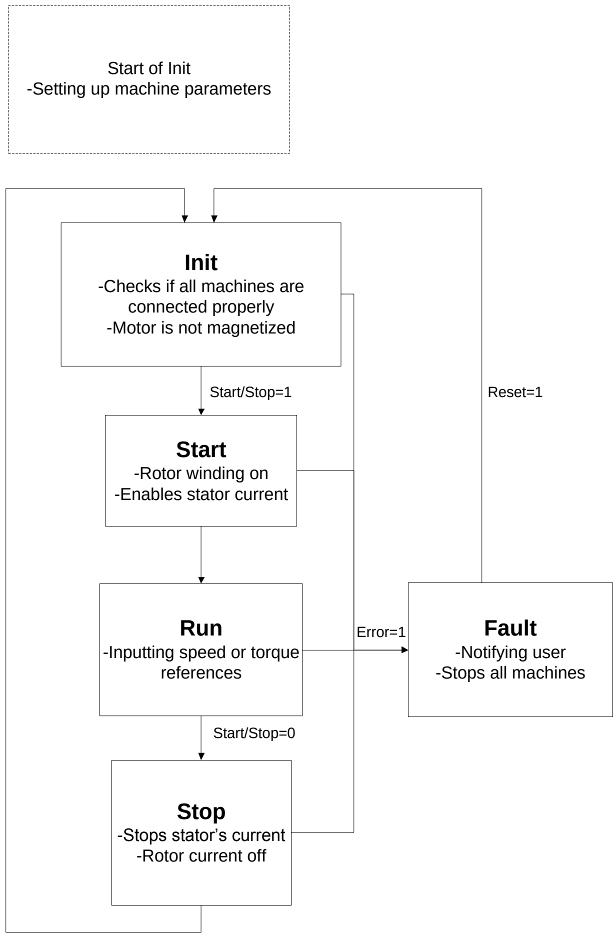

Figure 2.2 The simplified structure of the state machine used by the AC500 PLC.

The Start on Init state searches and transfers the constant values that are needed for the calculation of the excitation current and the overall control of the system from the ACS800 and DCS800 drives. The Start state starts the motor in a correct way described in Chapter 1.1.2. The Stop state stops the motor in a reverse order in comparison to the Start state. The Fault state actively shuts down the DC excitation current after the AC control signal is halted thus stopping the motor in a safe way. The overall structure of the system can be seen in Figure 2.1.

2.4 Functions

The main function and requirement of the automation system is to keep the motor running. This is achieved with active excitation current calculation and control. There is a PI controller in the PLC program, whose task is to keep the power factor near the value of 1 (i.e. at nominal cos φ), when the motor is operating in normal state. This enables the maximum torque and power to be transmitted to the motor shaft.

2.5 External Interfaces

The user interface has start and stop switches to start and stop the machine and an interface for user to give the desired torque and speed references to the system. The interface also contains local/remote buttons to change whether the machine is used locally from the automation AC500 or remotely. There also is a reset button to reset the errors and change the state machine's state back to the "Start on Init"-state. Figure 2.3 illustrates the concept version of the control panel with all the previously mentioned functionalities.

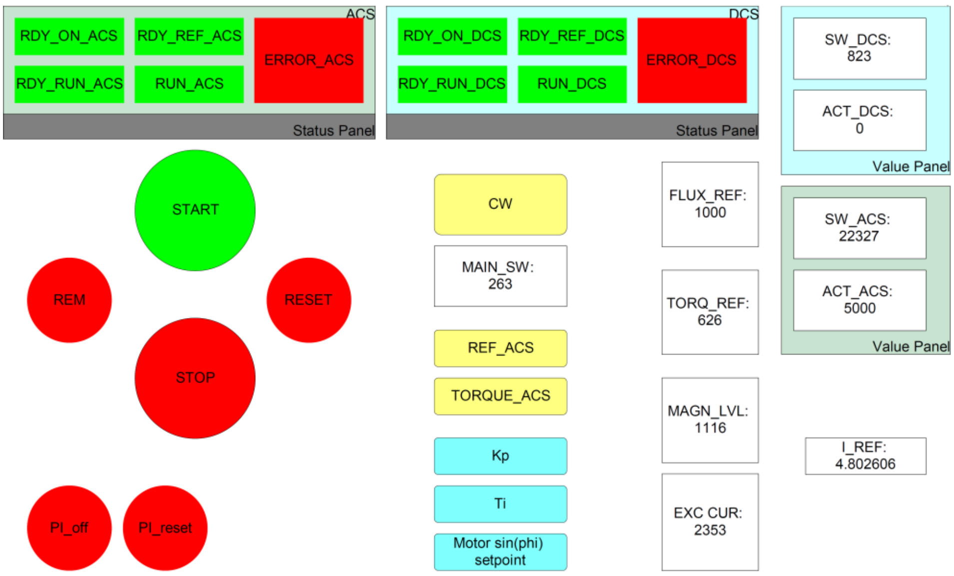

Figure 2.3 The concept's control panel with control switches, status and value panels.

2.5.1 Connections

The basic structure of the system's connections can be seen in Figure 2.1. The AC500 PLC is connected to main DC supply voltage source, and the LV synchronous machine's rotor is connected to the DCS800 DC drive. Both the AC and the DC drive are connected to 3-phase low voltage main grid.

The communication between the master PLC AC500 and the ACS800 and DCS800 slave devices is done by Profibus DP, and the data between the devices is sent by using PPO type 5. The AC500 sends control signals CW and reference REF values to both AC and DC drives. The drives then send the instantaneous actual values SW and ACT back to the master. The PPO type 5 also includes additional data in the PKW values that can be used for the configuration and initial setting in the "Start on Init" state.

2.6 Other Features

The performance requirements are calculated directly from the ACS800 PM control's capacities. The hypothesis that the motor is driven as a permanent magnet machine might cause some performance issues when the rotor's excitation current is changed during the run mode. The border conditions for such cases need to be calculated in the testing phase of the concept. The testing phase is described in full detail in (Tahvanainen, 2012).

3. INSTALLATION

This chapter describes the installation and configuration of the overall setup. Installation subchapter explains the general overview of the setup's wiring and communication. Parameter configuration subchapter briefly explains the most important parameters and the overall configuration of the system.

3.1 Installation of the setup

The simplified overall system structure can be seen in Figure 2.1. In more detail, the system consists of DCS800 DC drive, ACS800 frequency converter, externally excited synchronous motor, mains-frequency transformer and a load switch/contactor unit with ABB A50-30 contactors for controlling the 3-phase inputs and finally the AC500 PLC.

DCS800 drive's panel is connected to main (230 V) AC voltage two-phase source, and the rest of the drive is supplied from the 3-phase (400 V) AC mains-frequency transformer that is connected to the contactor controlled by the load switch. DCS800's output current is rectified with two diodes in the DCF506 overvoltage protection unit. There is also a resistor connected parallel with the motor's excitation circuitry (field winding) in the DCF506 to help further avoid issues with the returning current.

ACS800 is also supplied from the 3-phase current controlled by the load switch. The rest of the power needed comes straight from the 3-phase AC main supply.
The output signals from the ACS800 converter are sent to the synchronous motor's armature winding.

The synchronous motor is connected to the DCS800 and ACS800 drives as mentioned above. The motor is directly connected to the 3-phase AC main supply. The AC500 PLC is connected to a 24 V supply that is the AC500's CP-E 24/2.5 power supply.

A detailed description diagram of the laboratory setup is illustrated in Figure 3.1 and the overall laboratory setup applied in the project is illustrated in *APPENDIX I*.

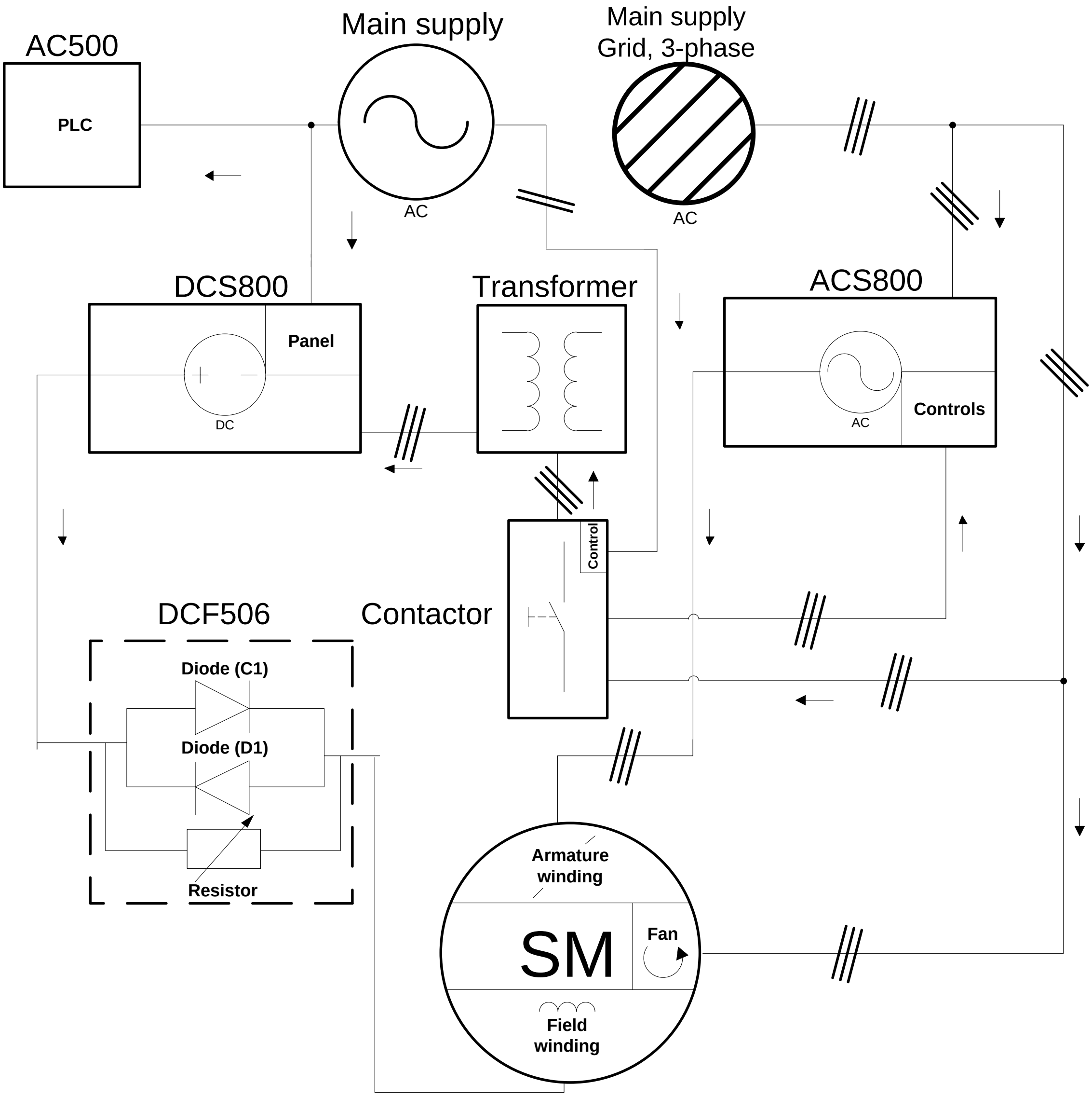

Figure 3.1 The overall setup's installation diagram.

AC500 and ACS800 form the terminating ends of the fieldbus connection, which is why their terminating resistors should be set to the "on" state to allow reliable communication. The Profibus cable connections can be seen in *APPENDIX I* where the purple Profibus cables stand out from the image. The terminating resistor connections are also illustrated in the Figure 2.2.

3.2 Parameter setting and configuration

This chapter explains the required parameter settings for the ACS800 and DCS800 drives for their use in the control of the synchronous motor. The required motor parameters for the field current control and the PI controller are given in Table 3.1. These parameters are some of the needed initialization parameters for the PLC program. The fully detailed description of the PLC and the parameters used in the PLC program are explained in (Niinimäki, 2012).

Table 3.1 Motor parameters used in field current control by the PLC program.

Parameter	Value (pu)
k_{ri}	4
l_{md}	1.05
l_{mq}	0.45
$l_{s\sigma}$	0.12

Besides the parameters listed in Table 3.2 for the ACS800 and DCS800 drives, both drives have to be initialized with the synchronous motor identification (ID) run procedure. In the ID run, the DCS800 field current controller is firstly configured, and after this the ACS800 ID run procedure is carried out by using a constant field excitation current for the synchronous motor.

DCS800's initialization run must be done in a stand-alone field exciter mode. Before setting the DCS800 to the stand-alone field exciter mode, the application macro (in parameter group 99) must be reset back to factory settings. After resetting the drive, the communication parameters in group 10 and 43 need to be set according to the ABB DCS800 Firmware manual (ABB, 2008). Then, the field current auto-tuning needs to be performed by setting the service mode parameter in group 99 to "field current auto-tune"-mode and start the machine.

When using the DCS800 in any field exciter mode configuration, an overvoltage protection unit such as DCF505 is mandatory. The field excited mode configuration setup is fully described in the Firmware manual (ABB 2008). The instructed stand-alone field exciter setup can be seen in Figure 3.2.

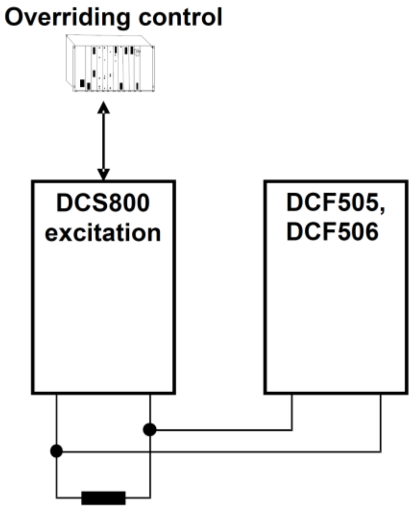

Figure 3.2 The DCS800 drive used in “stand-alone field exciter”-mode with the DCF505/06 overvoltage protection unit. (ABB 2008)

The important parameters used in both the ACS800 and DS800 drive’s communication are listed in the communication parameters initialization part of the Table 3.2. For the AC drive, the external communication reference is set in parameter 11.1, the communication profile is set as ABB drives, the communication module is set as Fieldbus, and the connection is in ring mode. DP mode is set to 1 so that all the words used in PPO-type 5 can be used in the communication, if necessary. Motor’s control mode is set to DTC as mentioned in Chapter 1 and the node address is set to 3 so that the addresses of the ring connected devices are in increasing order 1 for the PLC, 2 for the DCS800 and 3 for the ACS800.

Table 3.2 Important parameters used in configuration of the drive communication and initialization.

Communication parameters initialization

DRIVE	NAME	PARAMETER	VALUE
ACS800	EXT REF1 SELECT	11.1	EXT REF
	COMM PROFILE	16.11	ABB DRIVES
	ENCODER MODULE	98.1	RTAC-SLOT2
	COMM. MODULE	98.2	FIELDBUS
	CH0 HW CONNECTION	70.19	RING
	DP MODE	51.21	1
	MODULE TYPE	51.1	PROFIBUS DP
	Node address	51.2	3
	TORQUE SELECTOR	26.1	SPEED
	MOTOR CNTR MODE	99.8	DTC
	APPLICATION MACRO	99.11	FACTORY

DCS800	CommandSel	10.1	MainCtrlWord
	MODULE TYPE	51.1	PROFIBUS DP
	Node address	51.2	2
	DP MODE	51.21	1
	Ch0 HW Config	70.6	Ring
	CommModule	98.2	Fieldbus
	OperModeSel	43.1	FieldConv
	CurSel	43.2	CurRefExt

Reference and actual parameter settings

DRIVE	NAME	PARAMETER	VALUE
ACS800	PPO-type	51.4	5
	PZD3 OUT	51.5	2501
	PZD3 IN	51.6	107
	PZD4 OUT	51.7	306
	PZD4 IN	51.8	214
	PZD5 IN	51.10	213
	PZD6 IN	51.12	133
DCS800	PPO-type	51.4	5
	PZD3 OUT	51.5	4303
	PZD4 IN	51.8	116

Both drives use the Profibus DP communication profile described in Chapter 1.3.1, RPBA-01 Fieldbus communication module and the DP mode 1. In DCS800, the command selector needs to be set to “MainCtrlWord”, and the current selector to an external reference current “CurRefExt”, so that the excitation current calculated in the PLC’s PI-controller can be sent to the motor.

PZD3, 4, 5 and 6 are the input/output connections between the AC500 PLC and drives. PZD1 and 2, which are not configurable, contain the CW and SW values. From PZD3 and up, the parameters contain the reference REF and actual ACT values such as the excitation current, motor speed, torque etc. The parameters are configured using DriveWindow software, and the values are calculated by multiplying the parameter index such as the flux reference parameter 2.14 in ACS800 by 100 and getting an integer value of 214 which is then input to the ACS800 drive’s parameter 51.8. The parameters used in the ACS800 drive are fully described in (ABB, 2007), and the parameters for the DCS800 drive in (ABB, 2008).

4. SUMMARY

A working automation concept for an externally excited synchronous motor using a AC frequency converter and DC drive to drive the motor can be achieved without changing the firmware of the drives. The drives can be controlled with a PLC device and a suitable PLC program instead.

This concept used ABB's ACS800 and DCS800 drives and AC500 PLC to control a Hitzinger LV synchronous motor. The concept included planning the setup, making requirements specification for the overall functionality of the setup and for the PLC program, planning a suitable state machine, programming a PLC program, testing the PLC program, and making necessary tests to ensure the right functionality is met in accordance with the requirements specification and the state machine.

This thesis concentrated on the setup and requirements specification part of the concept. Lauri Niinimäki's bachelor thesis "Automation Concept for Electrically Excited LV Synchronous Motor: Implementation into AC500 Programmable Logic Environment" consists mostly some of the state machine planning and the whole PLC program and PI controller part of the concept. Arto Tahvanainen's bachelor's thesis "Electrically excited synchronous motor: Testing the automation concept" includes the testing phase of the concept. The overall concept's material can be therefore combined into a whole descriptive text.

The overall concept was successful by creating the automation setup that met the needed requirements, mostly being that the synchronous motor was able to be driven with the AC and DC drive without many problems. The motor was also successfully tested in the laboratory in standard constant use and the motor was running stable.

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