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Low-voltage Synchronous Generator Excitation Optimization and Design

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Synchronous generators are designed to match the customers' needs. Automated design and standardized solutions are necessary to simplify the modification of the generators for different customers and applications and to speed up the inquiry-offer process.

In this work, a solution for the excitation system of a low-voltage synchronous generator is designed. The excitation system is implemented with an auxiliary winding utilizing the power in air-gap flux-density harmonics to supply the automatic voltage regulator. A standard solution for the auxiliary winding and the voltage regulator system is created.

Different auxiliary winding solutions are studied and the optimal solution for the low-voltage synchronous generators is selected. The analytic dimensioning of the selected auxiliary winding solution is implemented as a computer program.

Requirements set for the excitation by different standards and classification societies are studied. The requirements for the auxiliary-winding supplied automatic voltage regulator are discussed and a solution for the voltage regulator system is implemented.

This thesis describes the selected solution for the low-voltage synchronous generator excitation system. The auxiliary winding solution, dimensioning process of the auxiliary winding and the automatic voltage regulator system are presented

The selected auxiliary winding solution utilizes the air-gap flux-density fundamental and third harmonic component to supply the excitation power. The fundamental is used in no-load and load operation and the third-harmonic component in generator short circuit. This is implemented with two different windings dimensioned independently for the on-load and short-circuit operation.

Using auxiliary-winding supplied excitation in low-voltage synchronous generators reduces the complexity of the automatic voltage regulator solution. Since two different supply frequencies are used, the operation of the regulator has to be based on a direct-current chopper converter instead of a thyristor bridge converter.

Keywords: automatic voltage regulator, auxiliary winding, dimensioning, excitation, low-voltage synchronous generator, optimization

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Tahtigeneraattorit suunnitellaan asiakkaiden tarpeiden mukaisesti. Automaattinen suunnittelu ja standardoidut ratkaisut ovat välttämättömiä generaattoreiden modifioimiseksi eri asiakkaille ja erilaisiin sovelluksiin sekä tilaus-tarjousprosessin nopeuttamiseksi.

Tässä työssä suunnitellaan matalajännitteisen tahtigeneraattorin magnetointijärjestelmä. Magnetointi toteutetaan apukäämillä, joka käyttää ilmavälivuontiheyden yliaaltojen tehoa automaattisen jännitteensäätäjän syöttämiseksi. Työssä luodaan standardoitu ratkaisu apukäämille ja jännitteensäätöjärjestelmälle.

Työssä tutkitaan erilaisia apukäämiratkaisuja ja valitaan optimaalinen ratkaisu matalajännitteiselle tahtigeneraattorille. Valitun apukäämiratkaisun analyyttinen mitoitus toteutetaan tietokoneohjelmana.

Eri standardien ja luokituslaitosten magnetoinnille asettamia vaatimuksia tutkitaan. Myös apukäämillä syötetyn automaattisen jännitteensäätäjän vaatimuksia pohditaan, ja jännitteensäätöjärjestelmälle luodaan ratkaisu.

Tämä diplomityö kuvaa matalajännitteiseen tahtigeneraattoriin valitun magnetointiratkaisun. Työssä esitetään apukäämiratkaisu, apukäämin mitoitusprosessi sekä automaattinen jännitteensäätöjärjestelmä.

Työssä valittiin apukäämiratkaisu, jossa magnetointiteho otetaan ilmavälivuontiheyden perusaallosta sekä kolmannesta yliaallosta. Perusaaltoa käytetään tyhjäkäynnissä ja kuormituksessa ja kolmatta yliaaltoa oikosulussa. Tämä toteutetaan kahdella eri käämillä, jotka mitoitetaan erikseen oikosulku- ja kuormitustilannetta varten.

Apukäämimagnetoinnin käyttäminen matalajännitteisissä tahtigeneraattoreissa yksinkertaistaa automaattista jännitteensäätäjäratkaisua. Kahta eri syöttötaajuutta käytettäessä käytettävän säätäjän tulee toimia katkojaperiaatteella tyristoritasasuuntaajan sijaan.

Avainsanat: apukäämi, automaattinen jännitteensäätäjä, magnetointi, matalajännitteinen tahtigeneraattori, mitoitus, optimointi

Preface

This thesis was carried out during the spring and summer of 2007 at ABB Oy, Electrical machines in Helsinki. It was part of the low-voltage synchronous generator development process in project Dragon.

Professor Antero Arkkio acted as the supervisor of this thesis. I wish to express my gratitude to him for the advice and comments related to my work. I also wish to thank my instructor Juha Kivioja for the guidance throughout the work as well as all the electrical designers who shared their knowledge and opinions and thus helped to complete my work.

Finally, I wish to thank my family for the support throughout my studies.

Helsinki, July 23rd 2007

Paavo Rasilo

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List of symbols and abbreviations

Symbols

a	number of parallel paths
A	linear current density
A_{Cu}	cross-sectional copper area of a wire
A_{i}	cross-sectional insulated area of a wire
A_{ins}	area of insulation in a slot
b	magnetic flux density
C	snubber capacitance
d	wire diameter
D	duty cycle
e	electromotive force
f	frequency
h	order of harmonic
I	current
i_{d}	rectifier diode current
j	number of effective turns per slot
J	current density
k	correction factor, safety factor
k_h	coil pitch factor
L'	effective length of the machine
m	number of phases
n	mechanical rotation frequency
N	number of turns
p	number of pole pairs
q	number of slots per pole and per phase
Q	number of slots
R	snubber resistance
t	time
THD	total harmonic distortion
U	voltage
u_{peak}	rectifier voltage peak
v	magnetomotive force
w	width
W	coil pitch
x	distance
X_{c}	commutation reactance in the exciter rotor
X''	subtransient reactance
α	thyristor firing angle
α'	diode firing delay angle
α_{slot}	slot angle
η	filling factor
ϑ	angle along the stator frame
Λ	air gap permeance
μ_{c}	commutation angle
τ_{p}	pole pitch
φ	magnetic flux

ξ_h	winding factor
ω	electrical angular frequency

Subscripts for symbols

a	auxiliary winding
AVR	automatic voltage regulator
d	d-axis
F	field winding
$h = 1, 2, \ldots$	harmonic
k	short circuit
m	exciter stator
max	maximum
min	minimum
p	pole
q	q-axis
r	exciter rotor

In case of windings, voltages, currents and frequencies, symbols with no subscript refer to the main machine.

Abbreviations

AVR	automatic voltage regulator
DNV	Det Norske Veritas
EMC	electromagnetic compatibility
emf	electromotive force
FEM	finite element method
IACS	International Association of Classification Societies
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
mmf	magnetomotive force
PMG	permanent magnet generator
rms	root mean square
SCR	silicon-controlled rectifier
THD	total harmonic distortion

1 Introduction

1.1 Overview

Synchronous generators are typically tailor-made to match the customers' needs. The modifications for different customers and applications must take place fast to speed up the inquiry-offer process. Thus automated generator design is a necessity.

A part of the generator design is the design of the excitation system. A standardized solution for the dimensioning and selection of the excitation system components is needed to simplify the design process and to give necessary information for the structural design of the machine.

The development of low-voltage synchronous generators was started by ABB Oy, Electrical machines in Helsinki in 2007. The excitation of the generators is to be implemented utilizing harmonic power by using an auxiliary winding mounted in the stator of the machine. Since the auxiliary winding excitation principle has not been used in Helsinki before, the excitation cannot be designed using the existing design tools.

1.2 Aim of the work

The main purpose of this work is to automate the optimization and design of the excitation system for a low-voltage synchronous generator. A design program is to be developed for dimensioning the auxiliary winding to supply the automatic voltage regulator, and a standard solution for the selection of the voltage regulator shall be created. This thesis will provide a theoretical basis for the excitation system design and present both the selected solutions for the design and the implementation of the design software. These main themes of this thesis are discussed in Chapters 2 - 6.

Chapter 2 gives an overview on low-voltage synchronous generators. The applications, requirements and main construction of the generators are discussed.

Chapter 3 presents the generator excitation construction and operation. An overview on the most common excitation methods of synchronous machines is given. A more detailed view is given at utilization of harmonic power in excitation of the low-voltage synchronous generator by using an auxiliary winding. The requirements for the performance of the generator excitation and regulation are considered in Chapter 4.

Chapter 5 gives an overview on the synchronous generator design. Existing design programs and methods are discussed. The excitation design for the low-voltage synchronous generator is discussed in Chapter 6. The implemented solutions for the design and optimization of the excitation system are presented.

The term 'low-voltage synchronous generator' discussed in this thesis refers to low-voltage synchronous generators developed by ABB Oy, Electrical machines.

2 Low-voltage synchronous generator

2.1 Applications

The low-voltage synchronous generator is a salient-pole synchronous generator with a rated voltage below 1000 V. Typical applications for the low-voltage synchronous generators are e.g. combined heat and power, stand by, peak shaving or continuous base load operation in stationary power stations, auxiliary power units and shaft generator systems in ships or offshore platforms. The generators are suitable for operation with diesel and gas engines, gas turbines and steam turbines. In this work, mainly marine diesel generators are considered.

As a standard, a low voltage generator is designed to have a rated power factor of 0,8 overexcited and frequency of 50 or 60 Hz. The maximum ambient temperature in marine applications is 50 ºC for the standard ratings but can be raised up to 60 ºC with derating. The maximum coolant water temperature in marine applications is 38 ºC but can be raised up to 48 ºC with derating. The minimum operating temperature is 0 ºC.

2.2 Requirements

The generators must meet the requirements set by several standardizing organizations such as International Electrotechnical Commission (IEC), National Electrical Manufacturers Association (NEMA), British Standards Institution (BSI), the Association for Electrical, Electronic & Information Technologies (VDE) and International Organization for Standardization (ISO). Considering this work, the noteworthy standards include IEC 60034-1 for rating and performance of rotating electrical machines containing electromagnetic compatibility (EMC) requirements for machines with rated voltage not exceeding 1000 VAC and IEC 60092 for electrical installations in ships.

In marine and offshore applications, the additional design criteria of the applicable classification society are also followed. These societies include American Bureau of Shipping (ABS), Bureau Veritas (BV), Chinese Classification Society (CCS), Det Norske Veritas (DNV), Germanischer Lloyds (GL), Korea Register of Shipping (KR), Lloyds Register (LR), Nippon Kyokai (NK), Registro Italiano Navale (RINA) and Russian Register of Shipping (RS). These societies are members of the International Association of Classification Societies (IACS).

The standards and classifications are discussed more carefully later considering requirements for the excitation system. In addition to the standards and classifications, different customer specifications must also be considered in generator design.

2.3 Construction

2.3.1 Frame

The frame is a modular rigid steel construction designed to withstand the vibrations and forces caused by the operation of the machine and to transfer them to the base. In addition to the normal operation of the machine, the frame and the attachments between the stator and frame must withstand the mechanical stresses caused by special situations, e.g. short circuits. The steel parts of the frame are either cast or welded and either welded or bolted together.

2.3.2 Stator

The stator core is made of stacked low-loss laminated electrical steel sheets with round-bottom slots. The stator plates are assembled from slotted segments. To ensure effective cooling of the stator, radial cooling ducts are left in the core.

The stator winding is made of random wound enameled round copper wires. The complete stator is impregnated to improve the mechanical firmness and the durability of the insulation of the winding.

2.3.3 Rotor

The salient-pole rotor consists of a shaft, poles fixed on the shaft, exciter rotor and a fan. The poles are stacked of pole sheets and bolted on the rotor. Star-shaped rotor sheets can be used for machines with lower pole numbers, in which case all the poles are connected to each other and the stacked rotor is shrink fitted on the shaft.

The excitation winding is made of enameled rectangular copper and wound around the rotor poles. The poles are supported by aluminium pole supports which ensures effective cooling of the rotor. The damper winding is a short-circuited cage winding and consists of bars of either copper or brass on the surface of the poles and connecting rings on both ends of the rotor.

2.3.4 Bearings

In low-voltage synchronous generators, antifriction ball or sleeve end shield bearings are used. When two bearings are used, one bearing is of locating and the other of non-locating type. In case of one bearing construction, the bearing is non-locating. The bearings are designed to have a theoretical life expectancy of more than 50 000 hours.

The lubrication can be of either self or forced type. In self lubrication, the oil is picked up by an oil lifting ring and transferred directly to the shaft. In forced lubrication, the oil is circulated to allow it to be cooled externally.

2.3.5 Cooling

The primary cooling medium is air. In open circuit cooling, the cooling air is taken directly from the ambient air in which the warm air is also transferred. In closed circuit cooling, air is circulated inside the machine and cooled using a heat exchanger in which the secondary cooling medium is usually water or air.

The air flow through the machine is obtained using a fan mounted on the shaft. In asymmetric cooling, the fan is located only at the other end of the machine and the air flows through the whole machine. In longer machines, symmetric cooling with a fan on both ends of the machine is used and the air flows through the air ducts of the stator.

2.3.6 Other parts

The standard equipment of low-voltage synchronous generators also includes the main terminal box and usually heating resistors to prevent condensation as well as temperature control elements in the stator, cooling system and bearings.

Additional equipment depends on the application and may include e.g. bearing vibration detection system, auxiliary terminal box, extra temperature sensors or different control systems for voltage regulators.

3 Generator excitation

3.1 Overview on excitation methods for synchronous machines

3.1.1 Direct-current excitation

Direct current supplied excitation (DC-AC excitation) is the most commonly used brushless excitation method in which the excitation power to the rotor is supplied by a separate excitation machine. The excitation machine is usually installed in the main frame and on the same shaft as the main machine.

The DC-AC excitation machine is a salient-pole external-pole generator that has its field winding in the stator and armature winding in the rotor. As the rotor rotates, the direct current supplied to the stator winding induces a three-phase alternating current into the rotor winding. This current is rectified into direct excitation current using a diode bridge installed in the rotor. The frequency of the rotor current before the rectifier is

$$f_{\mathrm{r}} = n p_{\mathrm{m}}, \tag{3.1}$$

where n is the mechanical rotation frequency of the rotor and p_{m} is the number of pole pairs in the excitation machine. The pole-pair number of the excitation machine is typically 13 or 17 which is larger than that of the main machine.

For the control of the voltage or reactive power of the main machine, the stator current is controlled by an automatic voltage regulator (AVR). The excitation power can be obtained using voltage and current transformers, an auxiliary winding installed in the stator slots of the main machine or a separate permanent magnet generator (PMG). In the first two cases, one of the stator poles must be a permanent magnet to enable self-excitation. In each case, instrument transformers for voltages and currents are needed for the regulator to control the voltage and power. The regulator and supply of the excitation power are considered later in this work. Figure 3.1 shows a schematic of DC-AC excitation without the measurement equipment.

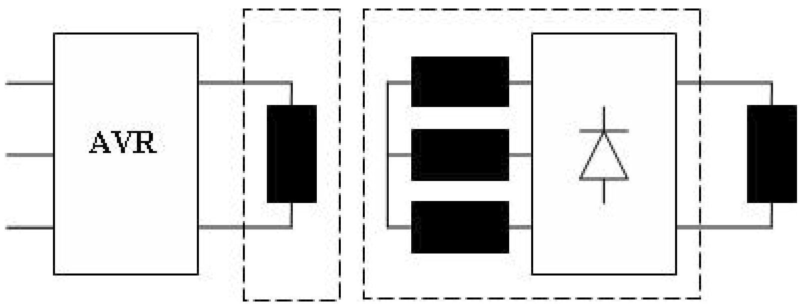

Figure 3.1 DC-AC excitation

DC-AC excitation is used in constant-speed synchronous-machine drives like generators and motors connected directly on line.

3.1.2 Alternating-current excitation

In alternating current supplied excitation (AC-AC excitation), the rotor of the excitation machine is similar to the rotor in DC-AC excitation. The stator has a three-phase winding which is supplied with alternating current using a supply transformer and a frequency converter. As the rotor rotates, a three-phase alternating current is induced into the rotor winding. Correspondingly to DC-AC excitation, this current is rectified into direct excitation current. Figure 3.2 shows a schematic of AC-AC excitation.

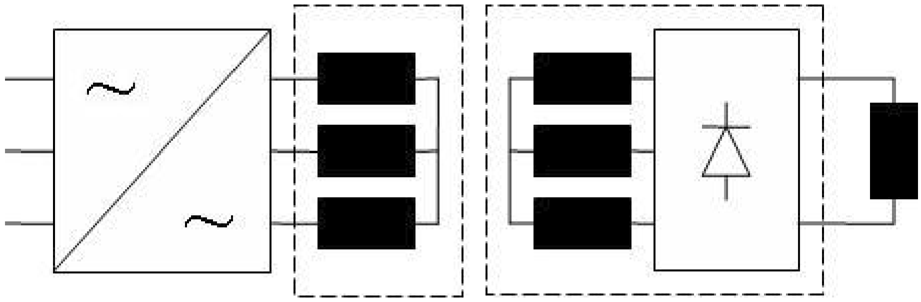

Figure 3.2 AC-AC excitation

AC-AC excitation is used in variable-speed synchronous-motor drives to produce the needed excitation power also when operating at low speeds or when the rotor is at rest.

3.1.3 Excitation with brushes

Before brushless excitation machines, an excitation was traditionally implemented using slip-rings with carbon brushes. Nowadays, this method is mainly used in high power variable speed motors running at a relatively slow speed. This allows faster excitation control in both positive and negative directions.

Slip-ring excitation equipment is significantly larger and more expensive than a brushless excitation machine. Slip rings need regular maintenance and the carbon dust from the brushes is harmful for the machine.

3.1.4 Permanent-magnet machine

In permanent-magnet machines, the excitation field is created using permanent magnets in the rotor. The permanent magnets can be mounted on the surface of the rotor, embedded into the surface or installed inside the rotor. The air gap is minimized to reduce the amount of magnet material needed.

Permanent magnets are used typically in medium- and low-power frequency-converter driven synchronous motor drives and in wind-turbine generators. The excitation implementation with permanent magnets is simple and durable but does not allow control of excitation or reactive power.

3.2 Excitation construction

3.2.1 Excitation machine

In low-voltage synchronous generators, brushless DC-AC excitation is used. The excitation machine is mounted inside the generator frame on to the non-drive end. The exciter stator has salient poles one of which is a permanent-magnet pole to obtain self-excitation in case the excitation power is not provided by a separate permanent-magnet generator. The permanent-magnet pole is magnetized during the manufacturing by using a winding wound around the pole

The exciter rotor is slotted and has a three-phase single-layer diamond winding with one slot per pole and per phase and each pole pair connected in parallel.

3.2.2 Rotating rectifier

The three-phase voltage induced into the exciter rotor winding is rectified and supplied to the main field winding. The rectifier is a six-pulse diode bridge mounted on the exciter rotor. A varistor protects the system from overvoltage peaks and a RC snubber damps the voltage peaks caused by the diodes. Figure 3.3 shows a schematic of the rectifier.

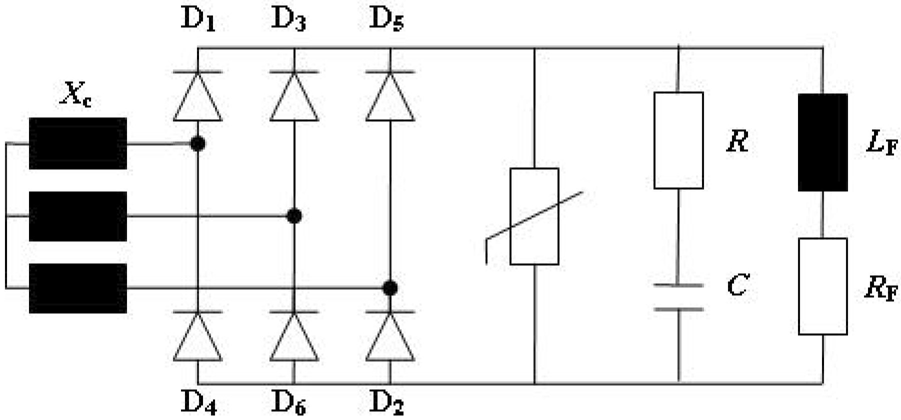

Figure 3.3 Rotating rectifier

Using the subtransient reactances of the excitation machine, the commutation reactance X_c can be approximated as

$$X_c = \frac{X''_{md} + X''_{mq}}{2}. \tag{3.2}$$

The commutation angle μ_c depending on the direct current I_d is given by

$$\mu_c = \arccos\left(1 - \frac{2X_c I_d}{\sqrt{2}U_r}\right), \tag{3.3}$$

where U_r is the armature voltage of the excitation machine. The commutation angle increases with the field current. With values of $\mu_c \geq 60^o$, a delay angle α' occurs before firing of a diode. Depending of these angles, the rectifier has three operating regions [1]:

1. $\mu_c < 60^o$, $\alpha' = 0$
2. $\mu_c = 60^o$, $0^o < \alpha' < 30^o$
3. $\mu_c > 60^o$, $\alpha' = 30^o$

Region 1 is the normal operation mode. The DC voltage and current of the rectifier are

$$U_d = \frac{3\sqrt{2}}{2\pi} U_r (1 + \cos \mu_c) \tag{3.4}$$

and

$$I_{\mathrm{d}} = \frac{\sqrt{2}U_{\mathrm{r}}}{X_{\mathrm{c}}}\left(1 - \cos\mu_{\mathrm{c}}\right). \tag{3.5}$$

In region 2, the firing of a diode is delayed since the previous commutation is still in progress and the voltage is insufficient. The voltage and current are given by

$$U_{\mathrm{d}} = \frac{3\sqrt{2}}{\pi}U_{\mathrm{r}}\frac{\sqrt{3}}{2}\cos\left(\alpha' + \frac{\pi}{6}\right) \tag{3.6}$$

and

$$I_{\mathrm{d}} = \frac{\sqrt{2}U_{\mathrm{r}}}{X_{\mathrm{c}}}\sin\left(\alpha' + \frac{\pi}{6}\right). \tag{3.7}$$

Region 2 may be reached when operating with higher field current values.

In region 3, two commutations occur at the same time and all the phases of the exciter rotor are short circuited. As the short circuit may damage the exciter machine, this operation mode must not be reached in any situation. Reduction of the subtransient reactances allows operation with higher field currents.

The RC snubber reduces the overvoltage and its rise speed in diode switch-off situations [2]. As a diode is turning off, a short reverse current occurs before total turn-off. This current flows through the commutation inductance. As the reverse current breaks, the commutation inductance forces the current to flow through another diode and the direction of the current on the DC side changes. Without the RC circuit, the current change in the field inductance causes a voltage of

$$u_{\mathrm{peak}} = L_{\mathrm{F}}\frac{di_{\mathrm{d}}}{dt}, \tag{3.8}$$

where i_{d} is the diode current. The RC snubber is used to conduct the current and to lower the voltage peak.

The varistor is used to protect the diode bridge from overvoltage peaks induced into the field winding. In transient states, like the generator short circuit, high DC current components in the stator winding induce high voltages into the field winding. Since the resistance of the varistor decreases rapidly as the voltage increases, it provides a low-resistance way to conduct the current and lowers the voltage over the diodes.

3.2.3 Automatic voltage regulator

The automatic voltage regulator is needed to control the voltage and the reactive power of the generator. The main tasks of the regulator are to control the voltage in the steady state, regulate the voltage under fault conditions and to facilitate reactive-power load-sharing between generators in parallel operation [3]. The voltage control is used in generators in island mode operation or in parallel operation with weak networks. Power factor is controlled in case the generator is operating in parallel with a strong network. In case of voltage control, the reactive power sharing between generators can be controlled additionally by using a reactive droop compensation method in which the voltage is lowered in the generator from which the reactive current flows. This lowers the need for excitation and thus also the reactive current.

The simplest analog automatic voltage-regulator solutions only control the excitation current in load operation. In more complex digital regulators, the control functions usually include power factor control, generator soft start capability, over-voltage and under-frequency protection, under- and overexcitation current limitation and voltage matching before synchronizing.

The AVR supplies and controls the current in the field winding of the exciter to provide the needed excitation current to the field winding in the rotor. The excitation is controlled typically by means of a PID control algorithm and a diode-bridge rectifier fed switch-mode power supply or a thyristor-bridge rectifier. The diode-bridge rectifier is a line-commutated converter in which the firing of the diodes depends only on the line voltage. The thyristor bridge is a self-commutated converter, and the thyristors must be fired to conduct the current. The thyristor-bridge rectifier is also called a silicon-controlled rectifier (SCR).

Typically, automatic voltage regulators can be supplied by either single or three-phase AC voltage or DC voltage. However, the excitation current output from the regulator may be limited to a value lower than the rated value when supplied with single-phase voltage. A higher current can be achieved with a single-phase supply by installing an external rectifier and a capacitor on the AVR mounting plate.

In case of a diode bridge rectifier and a buck converter, the excitation voltage is given by

$$U_{\mathrm{m}} = D\frac{3\sqrt{2}}{\pi}U_{\mathrm{a}}, \tag{3.9}$$

where U_{a} is the line-to-line voltage of a three-phase winding supplying the automatic voltage regulator and $D \in [0, 1]$ is the duty cycle of the buck converter. When a thyristor-bridge rectifier is used, the excitation voltage is

$$U_{\mathrm{m}} = \frac{3\sqrt{2}}{\pi}U_{\mathrm{a}}\cos\alpha, \tag{3.10}$$

where α is the firing angle of the thyristors. If the AVR is supplied by a single-phase winding with a voltage of U_{a}, the previous equations are replaced by

$$U_{\mathrm{m}} = D\frac{2\sqrt{2}}{\pi}U_{\mathrm{a}} \tag{3.11}$$

and

$$U_{\mathrm{m}} = \frac{2\sqrt{2}}{\pi}U_{\mathrm{a}}\cos\alpha. \tag{3.12}$$

In no-load operation, the AVR must provide a sufficient field current for the generator to produce the rated voltage at the rated speed. From no-load to full-load operation, the excitation current must be increased to compensate the effects of the armature reaction. In a generator short circuit, the AVR cannot limit the excitation current and all the power fed to the AVR is used in excitation. Thus the excitation current must be limited by other means in order to reduce the generator short-circuit current. This can be done by using a separate excitation current limiter.

Voltage and current transformers are needed to measure the instantaneous values of the main voltage and current to enable the voltage regulation. As the load current increases, the armature reaction reduces the air-gap flux and a voltage drop occurs in the terminals of the generator. The AVR must increase the excitation current to compensate the armature reaction and the voltage drops caused by the reactances of the machine.

The AVR is mounted in the main terminal box of the generator or on a mounting steel plate with its associated components inside a separate AVR box. As a standard in low-voltage synchronous generators, the automatic voltage regulator is supplied by a single-phase auxiliary winding. Supplying the excitation power is discussed in Section 3.3. Figure 3.4 presents a digital automatic voltage regulator.

Figure 3.4 Digital automatic voltage regulator

3.3 Harmonic excitation power

3.3.1 Overview

The excitation power to supply the automatic voltage regulator can be taken from the air-gap flux-density harmonics using an auxiliary winding mounted in the stator of the generator [4]. Similarly to the way that the flux-density fundamental induces a voltage into the main winding of the machine, the flux-density harmonics induce a voltage into the auxiliary winding. In low-voltage synchronous generator excitation, the fundamental and third harmonic flux component are utilized to produce the excitation power.

The auxiliary winding is wound into the stator slots together with the main winding and located on the top of the slot between the main winding and the air gap. Figure 3.5 shows a schematic of supplying the AVR with an auxiliary winding.

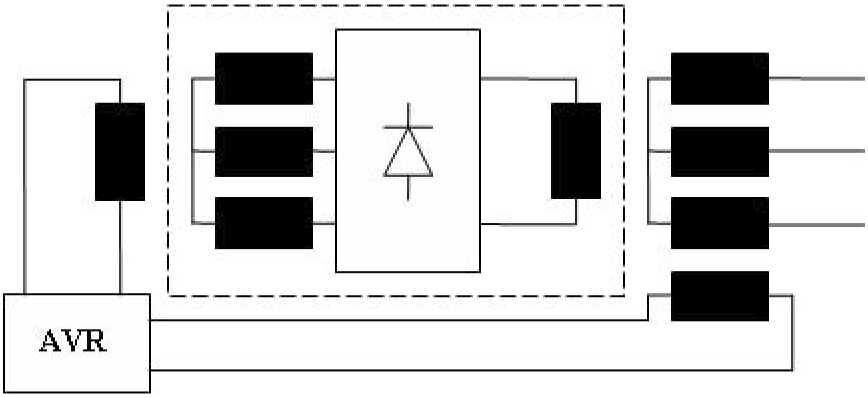

Figure 3.5 Excitation power supply with auxiliary winding

3.3.2 Winding factor

Since the stator winding is spatially distributed in the slots on the stator surface, the air-gap flux through different coils has a certain phase shift and the electromotive force (emf) induced into the winding can not be calculated using only the number of winding turns. Winding factor ξ_h must be used in calculation to take into account the construction of the winding and the flux-density harmonic components.

The emf induced into a coil is obtained as the geometric sum of the emfs induced into the positive and negative coil sides:

$$\vec{e} = \vec{e}_+ - \vec{e}_- . \tag{3.13}$$

The length of the emf vector of one coil side is equal to the emf induced into the coil side and the phase angle is the electrical angle along the stator frame that tells the location of the slot. The angle is obtained as a multiple of the slot angle

$$\alpha_{\mathrm{slot}} = p\frac{2\pi}{Q}, \tag{3.14}$$

where p is the number of pole pairs and Q is the number of slots. For one coil, the winding factor for flux-density harmonic h is obtained as the relation of the geometric and arithmetic sums of the emfs:

$$\xi_{h,\mathrm{coil}} = \sin\left(h\frac{\pi}{2}\right)\frac{\left|\vec{e}_+ - \vec{e}_-\right|}{\left|\vec{e}_+\right| + \left|\vec{e}_-\right|} . \tag{3.15}$$

For higher order harmonics, the angle of the voltage vector must also be multiplied by the order h of the harmonic. For N coils connected in series, the total winding factor is

$$\xi_h = \sin\left(h\frac{\pi}{2}\right)\frac{\sum_{i=1}^{N}\left|\left(\vec{e}_+ - \vec{e}_-\right)\right|}{\sum_{i=1}^{N}\left(\left|\vec{e}_+\right| + \left|\vec{e}_-\right|\right)} . \tag{3.16}$$

For several different winding constructions, Equation (3.16) can be expressed using the phase number m, number of slots per pole and per phase q, coil pitch W and pole pitch τ_p. For a 2-layer integer-slot winding, the winding factor is

$$\xi_h = \frac{\sin\left(h\frac{\pi}{2m}\right)}{q\sin\left(h\frac{\pi}{2mq}\right)} k_h \,, \tag{3.17}$$

where

$$k_h = \sin\left(h\frac{W}{\tau_\mathrm{p}}\frac{\pi}{2}\right) \tag{3.18}$$

is the coil pitch factor. For a 2-layer fractional-slot winding with the number of slots per pole and per phase of

$$q = k + \frac{1}{2}, k \in \mathrm{N} \,, \tag{3.19}$$

the winding factor is

$$\xi_h = \frac{\sin\left(h\frac{\pi}{2m}\right)}{2q\sin\left(h\frac{\pi}{4mq}\right)} k_h \tag{3.20}$$

for odd values of h.

3.3.3 Flux-density harmonics

In synchronous generators, the air gap flux-density harmonics arise from two causes:

1. the non-sinusoidal distribution of the winding and
2. the permeance variations over the air gap.

The winding is concentrated in the slots and around the salient poles, which causes the magnetomotive force (mmf) in the air gap to be non-sinusoidal. The permeance variations in the air gap are caused by the slot openings in the stator, salient poles in the rotor, saturation of the core and eccentricity of the rotor [5].

The magnetic flux in the air gap is the product of the air-gap mmf v and the air-gap permeance Λ. The flux density is given by

$$b = \frac{v\Lambda}{\tau_\mathrm{p} L'} \,, \tag{3.21}$$

where $\tau_\mathrm{p} L'$ is the area of one pole through which the flux flows. The flux-density harmonics arise from the harmonic contents in both the mmf and permeance. The total air-gap mmf results from the currents in both the stator winding and the field winding in the rotor. The most important source of the permeance variations is the saliency of the rotor poles. In the following, these three sources of the flux-density harmonics are studied considering the fundamental and third harmonic flux density component.

Both time and space harmonics are relevant when considering the flux density. Term 'time harmonic' refers to the rotating flux-density field in the air gap. Term 'space harmonic' refers to the spatial air-gap flux-density distribution.

Harmonics due to stator winding

In the stator frame of reference, the mmf v caused by an m-phase stator winding with a current I is a function of time and the angle ϑ along the stator frame. Here, distance x along the stator frame will be used instead of angle ϑ. The distance is

$$x = \frac{d_s}{2}\vartheta = \frac{p\tau_p}{\pi}\vartheta, \tag{3.22}$$

where d_s is the inner diameter of the stator and p is the number of pole pairs. When the mmf-axis is set in the middle of the first coil in a coil group as in Figure 3.6, the mmf of the stator winding can be written using a Fourier cosine series as

$$v_s = v_{s,0} + \sum_{h=1}^{\infty} \hat{v}_{s,h} \cos\left(h\pi \frac{x}{\tau_p} - \omega t - \phi_s + \beta \right), \tag{3.23}$$

where ω is the synchronous frequency, ϕ_s is the phase angle between the current and the phase voltage and β is an angle depending on the winding construction [5].

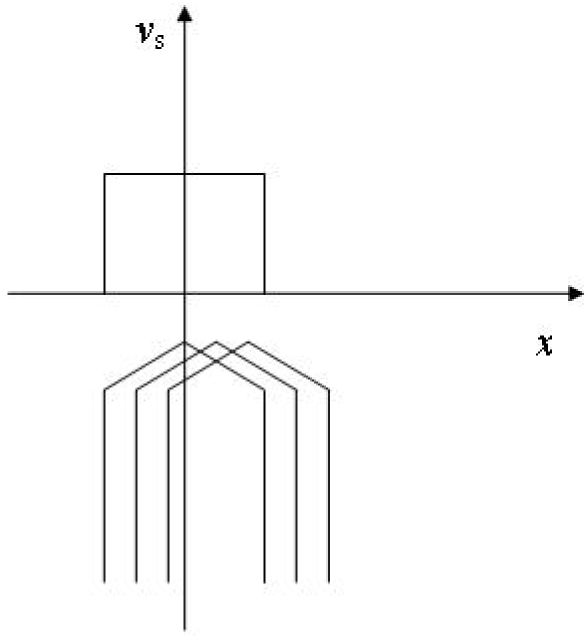

Figure 3.6 Location of the mmf-axis and the mmf of the first coil

The amplitude of a harmonic is given by

$$\hat{v}_{s,h} = \sqrt{2} I \frac{m}{hp\pi} \xi_h N. \tag{3.24}$$

The low-voltage synchronous generators have a three-phase main winding in the stator, and the total air-gap mmf is the sum of the mmfs caused by different phases. As these are summed, the third harmonic components in each mmf neglect each other and no third harmonic mmf component is generated due to the stator current. Thus, considering this work, the mmf of the stator winding can be assumed to be purely sinusoidal and can be expressed as

$$v_{\mathrm{s}} = \hat{v}_{\mathrm{s},1} \cos\left(\pi \frac{x}{\tau_{\mathrm{p}}} - \omega t - \phi_{\mathrm{s}} + \beta \right). \tag{3.25}$$

In the previous equations, the stator slots were assumed to be of negligible width. When the finite slot width w_{slot} is taken into account, the amplitude must be multiplied by factor

$$k_{\mathrm{slot}} = \frac{\sin\left(\frac{w_{\mathrm{slot}}}{\tau_{\mathrm{p}}} \frac{\pi}{2} \right)}{\frac{w_{\mathrm{slot}}}{\tau_{\mathrm{p}}} \frac{\pi}{2}}. \tag{3.26}$$

Angle β for this winding is given by

$$\beta = \frac{\pi}{6h}\left(\frac{1}{q} - 1 \pm \frac{1}{2q} \right). \tag{3.27}$$

In fractional-slot windings, the minus sign is used when the mmf-axis is set in the middle of the first coil of the wider zone and the plus sign in case of the narrower zone.

Harmonics due to field winding

To define the mmf harmonics caused by the field winding of the rotor, the winding is assumed to fill the whole space between the pole tip and the pole arc. The linear current density A_{F} of the field winding is presented in Figure 3.7.

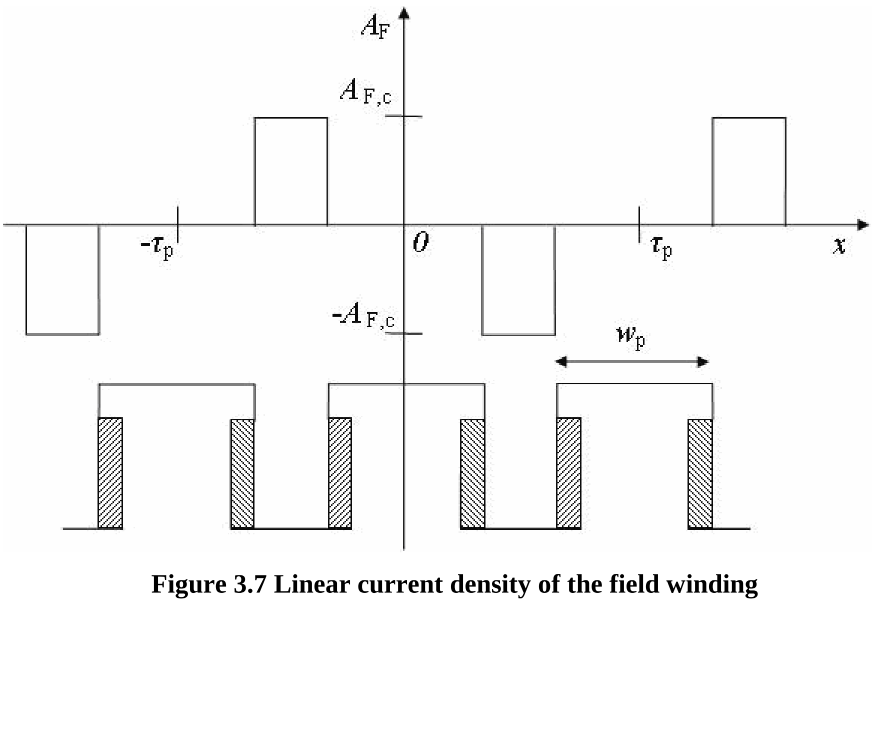

Figure 3.7 Linear current density of the field winding

Since the linear current density axis is set in the middle of the pole, the current density can be expressed using a Fourier sine series. If x is the distance along the rotor frame and the width of the pole is denoted by w_p, the linear current density in the rotor frame of reference is given by

$$A_\mathrm{F} = \sum_{h=1}^{\infty} \hat{A}_{\mathrm{F},h} \sin\left(h\pi \frac{x}{\tau_\mathrm{p}}\right). \tag{3.28}$$

where the amplitudes of the harmonics are

$$\begin{aligned}\hat{A}_{\mathrm{F},h} &= \frac{1}{\tau_\mathrm{p}} \int_{-\tau_\mathrm{p}}^{\tau_\mathrm{p}} A_\mathrm{F} \sin\left(h\pi \frac{x}{\tau_\mathrm{p}}\right) dx = -A_\mathrm{F,c} \frac{4}{\tau_\mathrm{p}} \int_{\frac{w_\mathrm{p}}{2}}^{\tau_\mathrm{p} - \frac{w_\mathrm{p}}{2}} \sin\left(h\pi \frac{x}{\tau_\mathrm{p}}\right) dx \\ &= A_\mathrm{F,c} \frac{4}{\pi h}\left[\cos\left(h\pi \frac{w_\mathrm{p}}{2\tau_\mathrm{p}}\right) - \cos\left(h\pi \frac{2\tau_\mathrm{p} - w_\mathrm{p}}{2\tau_\mathrm{p}}\right)\right].\end{aligned} \tag{3.29}$$

The constant linear current density between the poles is

$$A_\mathrm{F,c} = \frac{\frac{N_\mathrm{F}}{a_\mathrm{F}} I_\mathrm{F}}{\tau_\mathrm{p} - w_\mathrm{p}}, \tag{3.30}$$

where N_F and a_F are the number of turns and number of parallel paths in the field winding and I_F is the excitation current. Since the linear current density distribution is half-wave symmetrical, no even harmonics exist in the spectrum.

The field winding mmf is obtained by integrating the linear current density. The mmf is

$$v_\mathrm{F} = \int A_\mathrm{F} dx = \sum_{h=1}^{\infty} \int \hat{A}_{\mathrm{F},h} \sin\left(h\pi \frac{x}{\tau_\mathrm{p}}\right) dx = -\sum_{h=1}^{\infty} \hat{v}_{\mathrm{F},h} \cos\left(h\pi \frac{x}{\tau_\mathrm{p}}\right), \tag{3.31}$$

where

$$\hat{v}_{\mathrm{F},h} = \hat{A}_{\mathrm{F},h} \frac{\tau_\mathrm{p}}{\pi h}. \tag{3.32}$$

The mmf is presented in Figure 3.8.

In the stator frame of reference, the mmf varies with time as the rotor rotates. The mechanical speed of the rotor is denoted by ω_m. When transforming the previous equations into stator frame of reference, distance x must be replaced with

$$x \to x - \frac{d_\mathrm{s}}{2} \omega_\mathrm{m} t = x - \frac{2p\tau_\mathrm{p}}{2\pi} \omega_\mathrm{m} t = x - \frac{\tau_\mathrm{p}}{\pi} \omega t, \tag{3.33}$$

where d_s is the inner diameter of the stator and

$$\omega = p\omega_{\mathrm{m}} \tag{3.34}$$

is the synchronous frequency. The time- and space-dependent mmf in the stator frame of reference is

$$v_{\mathrm{F}} = -\sum_{h=1}^{\infty} \hat{v}_{\mathrm{F},h} \cos\left(h\pi \frac{x}{\tau_{\mathrm{p}}} - h\omega t \right). \tag{3.35}$$

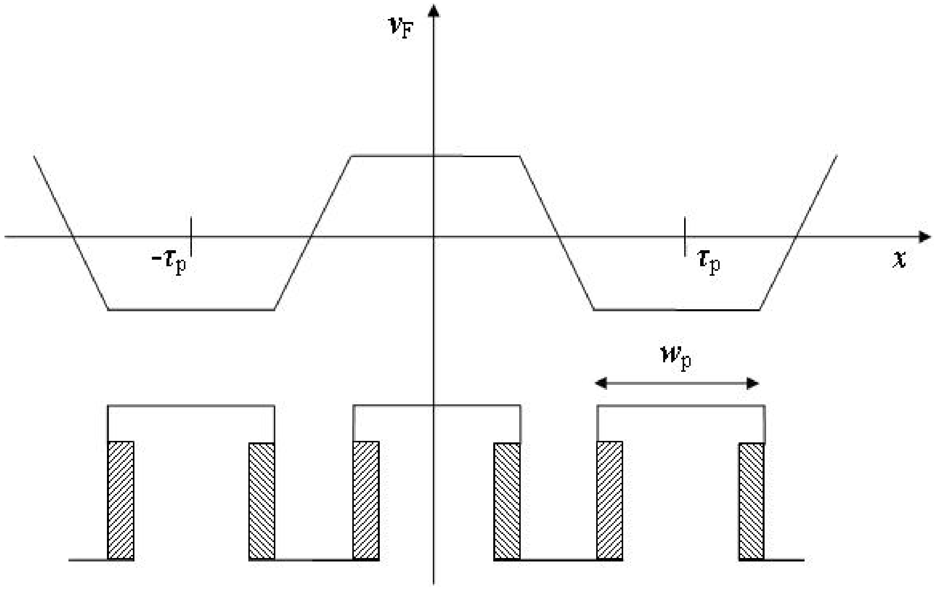

Figure 3.8 Mmf caused by the field winding

Harmonics due to salient rotor poles

To define the permeance harmonics caused by the salient poles of the rotor, the stator surface is assumed to be smooth, or the stator slotting is not taken into account. The rotor pole shoe is assumed to be round with an air gap of constant length. The permeance is approximated to be constant over a pole and zero outside the pole. The approximation is shown in Figure 3.9.

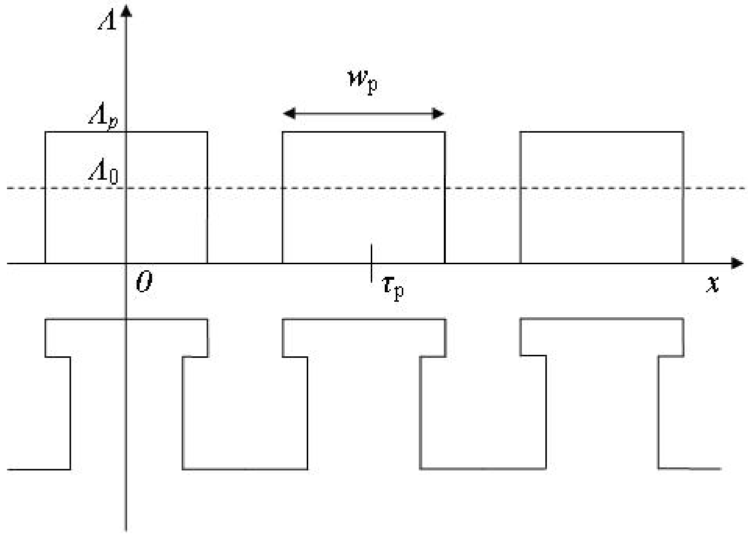

Figure 3.9 Permeance variation due to salient rotor poles

Since the permeance axis is set in the middle of the rotor pole, the permeance can be expressed using a Fourier cosine series. The permeance is given by

$$\Lambda = \Lambda_0 + \sum_{h=1}^{\infty} \hat{\Lambda}_h \cos\left(2h\pi \frac{x}{\tau_p}\right), \tag{3.36}$$

where

$$\Lambda_0 = \frac{1}{\tau_p} \int_{-\frac{\tau_p}{2}}^{\frac{\tau_p}{2}} \Lambda dx = \Lambda_p \frac{1}{\tau_p} \int_{-\frac{w_p}{2}}^{\frac{w_p}{2}} dx = \Lambda_p \frac{w_p}{\tau_p} \tag{3.37}$$

is the average permeance, and the amplitudes of the harmonics are given by

$$\begin{aligned} \hat{\Lambda}_h &= \frac{2}{\tau_p} \int_{-\frac{\tau_p}{2}}^{\frac{\tau_p}{2}} \Lambda \cos\left(2h\pi \frac{x}{\tau_p}\right) dx \\ &= \frac{2}{\tau_p} \Lambda_p \int_{-\frac{w_p}{2}}^{\frac{w_p}{2}} \cos\left(2h\pi \frac{x}{\tau_p}\right) dx = \Lambda_p \frac{2}{\pi h} \sin\left(h\pi \frac{w_p}{\tau_p}\right). \end{aligned} \tag{3.38}$$

When saturation is not taken into account, the constant permeance over a pole is

$$\Lambda_p = \mu_0 \frac{\tau_p L'}{\delta''}, \tag{3.39}$$

where the equivalent air gap is obtained by multiplying the actual air gap δ with the the Carter's coefficient k_C:

$$\delta'' = k_C \delta. \tag{3.40}$$

In stator frame of reference, the permeance also varies with time in a similar manner as the field-winding mmf. Using Equation (3.33), the time- and space-dependent permeance is

$$\Lambda = \Lambda_0 + \sum_{h=1}^{\infty} \hat{\Lambda}_h \cos\left(2h\pi \frac{x}{\tau_p} - 2h\omega t\right). \tag{3.41}$$

The half-waves of the permeance distribution are not symmetrical and both even and odd harmonics exist in the permeance spectrum.

Flux density

The flux density is obtained as a product of the total mmf and permeance:

$$b = \frac{1}{\tau_\mathrm{p} L'} \left[\hat{v}_{\mathrm{s},1} \cos\left(\pi \frac{x}{\tau_\mathrm{p}} - \omega t - \phi_\mathrm{s} + \beta \right) - \sum_{h=1}^{\infty} \hat{v}_{\mathrm{F},h} \cos\left(h\pi \frac{x}{\tau_\mathrm{p}} - h\omega t \right) \right] \times$$
$$\times \left[\Lambda_0 + \sum_{h=1}^{\infty} \hat{\Lambda}_h \cos\left(2h\pi \frac{x}{\tau_\mathrm{p}} - 2h\omega t \right) \right]. \tag{3.42}$$

The flux density consists of both time and space harmonics. The magnitude of the induced voltage is proportional to the frequency of the harmonic and thus higher order time harmonics induce higher voltages in the auxiliary winding. The winding is designed to utilize the first- and third-order space harmonics. In the following, the magnitudes of these harmonics are defined.

Since the harmonics in both the mmf and permeance are cosinusoidal, and the product of two cosines gives

$$\cos x_1 \cos x_2 = \frac{1}{2}\left[\cos(x_1 + x_2) + \cos(x_1 - x_2)\right] \tag{3.43}$$

for $x_1, x_2 \in \mathrm{R}$, the harmonic frequencies in the flux density are obtained as the sum and difference of the frequencies in the mmf and permeance. As the amplitudes of the mmf and permeance harmonics are inversely proportional to their number of order, only the lowest order harmonics have significant effect on the total flux density. Here, only the harmonics with $h \leq 3$ are taken into account.

Only the air-gap permeance distribution has even harmonic components and thus the odd flux density harmonics can only be formed of odd mmf harmonics and even permeance harmonics. Since the permeance varies periodically with a fundamental period of one pole pair, the flux-density space fundamental can be obtained either as the product of the mmf fundamental and constant permeance or the third mmf harmonic and second permeance harmonic. Combining these using Equation (3.43) yields

$$b_1 = \frac{\hat{v}_{\mathrm{s},1}\Lambda_0}{\tau_\mathrm{p} L'} \cos\left(\pi \frac{x}{\tau_\mathrm{p}} - \omega t - \phi_\mathrm{s} + \beta \right) -$$
$$- \frac{\hat{v}_{\mathrm{F},1}\Lambda_0}{\tau_\mathrm{p} L'} \cos\left(\pi \frac{x}{\tau_\mathrm{p}} - \omega t \right) -$$
$$- \frac{\hat{v}_{\mathrm{F},3}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'} \cos\left(\pi \frac{x}{\tau_\mathrm{p}} - \omega t \right). \tag{3.44}$$

The third space harmonic can be obtained either as the product of the third mmf harmonic and constant permeance or the mmf fundamental and second permeance harmonic. Combining these yields

$$
\begin{aligned}
b_3 = {} & \frac{\hat{v}_{\mathrm{s},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t + \phi_\mathrm{s} - \beta\right) - \\
& - \frac{\hat{v}_{\mathrm{F},3}\Lambda_0}{\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t\right) - \\
& - \frac{\hat{v}_{\mathrm{F},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t\right).
\end{aligned} \tag{3.45}
$$

The derivation of Equations (3.44) and (3.45) is presented in Appendix 1. It can be seen that the order of a harmonic refers to both the time and space dependencies of the flux density. Thus, from now on, subscript $h \in \mathrm{N}$ is used to depict the order of both the time and space harmonics at the same time.

The previous study gave an approximation for the magnetic flux density in the air gap taking into account the magnetomotive forces caused by the stator winding and field winding and the permeance variations due to the salient rotor poles. Because of the simplifications made, the approximation is not very accurate and may not be directly applicable to flux-density harmonic calculation. However, it describes a few basic reasons behind the flux-density harmonics, and the analysis may be extended in order to have more specific results. The following gives a short description of other sources of flux-density harmonics more accurate analysis of which is beyond this work.

Other harmonics

The flux-density harmonics caused by the saturation of the core, the combination of the mmf and the stator slot openings and the eccentricity of the rotor also rotate in the stator frame of reference. Hence, they also could be utilized to obtain excitation power.

The harmonics caused by saturation are similar to those caused by the salient rotor poles. The saturation can be taken into account by enlarging the actual air gap to a value where the entire mmf of the magnetic circuit can be thought to affect only this longer equivalent air gap. After this, the magnetic flux density in the equivalent air gap equals the flux density in the actual air gap. The saturation of the stator and rotor yokes corresponds to adding a constant value to the actual air gap length. The teeth are most saturated near the peak of the flux density and the air gap must be enlarged more in that area.

Rotor eccentricity is divided in two different types. In static eccentricity, the rotor is located symmetrically around the shaft but the shaft itself is eccentrically mounted in the stator bore. In dynamic eccentricity, the shaft is in the middle of the stator bore but the rotor is eccentrically installed around the shaft. Usually both eccentricities take place at the same time but the other type is dominant to the other.

3.3.4 Induced voltage

A voltage is induced into a coil through which a changing flux flows. Since the flux through a coil is obtained as a space integral of the flux density, only time harmonics are relevant when considering the flux and the term ‘flux harmonic’ always refers to a time harmonic.

A single flux harmonic through a coil varies sinusoidally with time:

$$\varphi_h = \tau_\mathrm{p} L' b_h = \hat{\varphi}_h \sin(h\omega t + \phi_h). \tag{3.46}$$

Since h denotes the order of both the time- and space-dependent flux-density harmonics, the electromotive force induced into a winding by the time-dependent flux harmonic h is

$$e_h = -N\xi_h \frac{d\varphi_h}{dt} = -h\omega N\xi_h \hat{\varphi}_h \cos(h\omega t + \phi_h) \tag{3.47}$$

$$\Rightarrow U_h = h\omega N\xi_h \frac{\hat{\varphi}_h}{\sqrt{2}}, \tag{3.48}$$

where U_h is the rms voltage. Since a single space harmonic in the flux density is sinusoidal, the average flux density over one pole is

$$b_{h,\mathrm{av}} = \frac{2}{\pi}\hat{b}_h \tag{3.49}$$

and

$$\hat{\varphi}_h = b_{h,\mathrm{av}} \tau_\mathrm{p} L' = \frac{2}{\pi}\hat{b}_h \tau_\mathrm{p} L' \tag{3.50}$$

is obtained as the amplitude of the flux through the pole [6]. Combining Equations (3.48) and (3.50) yields

$$U_h = h\omega N\xi_h \frac{2}{\pi}\tau_\mathrm{p} L' \frac{\hat{b}_h}{\sqrt{2}} \tag{3.51}$$

for the harmonic voltage induced into the winding. The total number of turns is obtained using the number of pole pairs p, number of slots per pole and per phase q, number of effective turns per slot j and the number of parallel paths a:

$$N = \frac{pqj}{a}. \tag{3.52}$$

3.3.5 Auxiliary winding

The auxiliary winding is designed to utilize the air-gap flux-density harmonics to supply the excitation power to the automatic voltage regulator. The auxiliary winding is wound into the stator slots together with the main winding. It is located on the top of the slot near the air gap. Figure 3.10 shows an example of an auxiliary winding wound into the stator.

In no-load operation, the terminal voltage of the generator is induced by an almost purely sinusoidal flux time harmonic. Clearly, this fundamental can also be utilized to obtain the excitation power in no-load operation. As the load increases, the armature current and the saturation of the machine cause higher order harmonics to arise and also these harmonics can be used in excitation. In generator short circuit, the flux is highly distorted and contains a relatively high third harmonic component which should be utilized to provide the excitation power needed in short circuit [4].

The auxiliary winding must be designed to utilize the chosen flux-density harmonics in different situations. The coil pitch factor in Equation (3.18) determines the voltage induced by a certain flux-density harmonic. In [7], a possible solution for an auxiliary winding utilizing the first, third, fifth and seventh harmonic is presented. However, for the auxiliary winding solution to remain as simple as possible, only the minimum number of harmonics needed should be utilized. As mentioned, utilizing the fundamental and the third harmonic should be enough in no-load, load and short-circuit operation.

Figure 3.10 Auxiliary winding mounted into the stator slots

Different winding constructions

For low-voltage synchronous generators, only the lowest order harmonics are to be utilized to obtain the excitation power. For the solution to remain as simple as possible, only a single-phase auxiliary winding will be used. In the following, three different winding constructions are studied considering the low-voltage synchronous generator excitation.

Construction 1 presents an existing auxiliary winding solution utilized in some smaller sized synchronous generators. It only utilizes the third flux-density harmonic for excitation.

In Construction 2, an attempt is made to study the principles of utilization of both the flux fundamental and the third harmonic in excitation.

Being slightly different from Construction 2, Construction 3 also utilizes the fundamental and the third harmonic and guarantees better results considering the excitation also in generator short circuit.

Results of voltage waveform simulations for each auxiliary winding construction are presented in Subsection 3.3.6.

Example machine

In the following examples of different auxiliary winding constructions, a 113 kVA low-voltage synchronous generator with a rated voltage of 400 V and frequency of 50 Hz is studied. The main winding is a 4-pole, 2-layer slot-pitch shifted integer-slot winding. The total number of slots is 48 and the coil pitch is 9.

The flux-density harmonics in no-load and short-circuit operation for the example machine were calculated using a finite-element method calculation program FCSMEK. The program is discussed in more detail later in Subsection 5.2.3. The amplitudes of the flux-density harmonics are presented in Table 3.1.

Table 3.1 Flux density harmonics in no-load and short-circuit operation

	Fundamental $\hat{b}_1$ (T)	**Third harmonic $\hat{b}_3$ (T)**
No load	0,91	0,03
Short circuit	0	0,17

The no-load operation was simulated using the rated voltage. In the short-circuit simulation, the generator was excited so that the magnitude of the armature current was three times the nominal value. This is an important generator excitation requirement for the circuit breakers to operate in case of short circuit.

Notations

Windings with different coil pitches can be used to obtain the excitation power. The following denotations are used when considering the auxiliary winding construction:

H_1: a coil with the coil pitch W_{H1} close to the pole pitch and

H_3: a coil with the coil pitch W_{H3} close to one third of the pole pitch.

To allow winding of one coil of H_1 or three coils of H_3 over one pole area, the coil pitch of both coils is reduced by one slot. In Figure 3.11, the winding of the example machine with coils H_1 and H_3 and the used drawing symbols are presented.

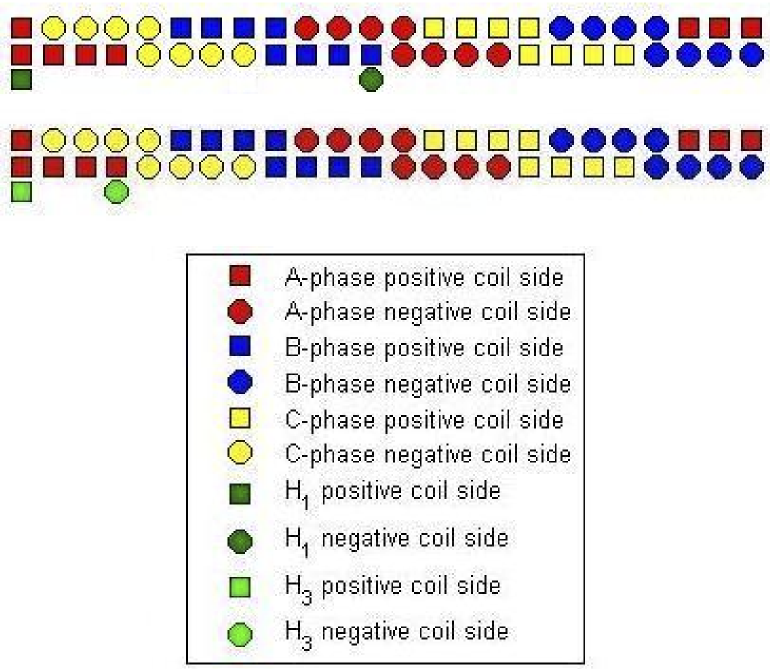

Figure 3.11 Main winding and coils H_1 and H_3

Only the symmetrical part of the main stator winding is presented in the following examples. The auxiliary winding may be symmetrically wound into the stator or only installed in the area of the shown pole pair. In either case, the construction of the auxiliary winding is mentioned separately.

Phase of harmonics

In the following examples, the third flux-density harmonic is presented in the same phase as the fundamental component. The third harmonic in load operation is mostly caused by saturation. As mentioned earlier, the stator teeth are most saturated near the peak of the flux density wave. This lowers the peak as can be seen in Figure 3.12. The figure shows that the flattened flux-density wave consists of the fundamental and a third harmonic component that has a negative value near the peak of the fundamental. Thus, in load operation, the fundamental and third harmonic flux-density component can be assumed to have the same phase angle.

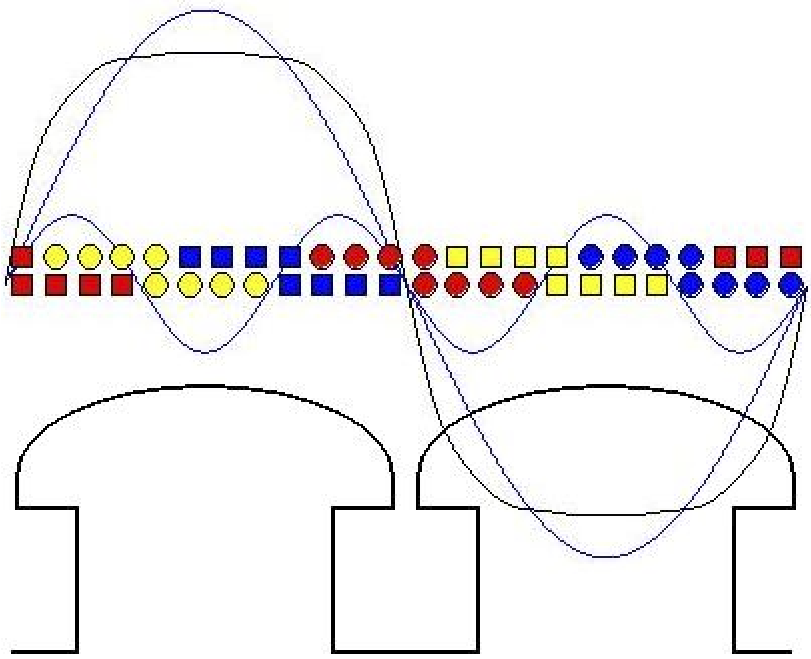

Figure 3.12 Third harmonic caused by saturation

Construction 1: Winding for the third harmonic

Figure 3.13 shows a diagram of an auxiliary winding designed to utilize only the third flux-density harmonic. The winding consists of total of 12 coils symmetrically wound into the whole stator and connected in series. Since the third flux-density harmonic flows entirely through the third harmonic winding, the winding factor calculated using Equation (3.16) is close to one and nearly the maximum possible voltage is induced by the third flux-density harmonic.

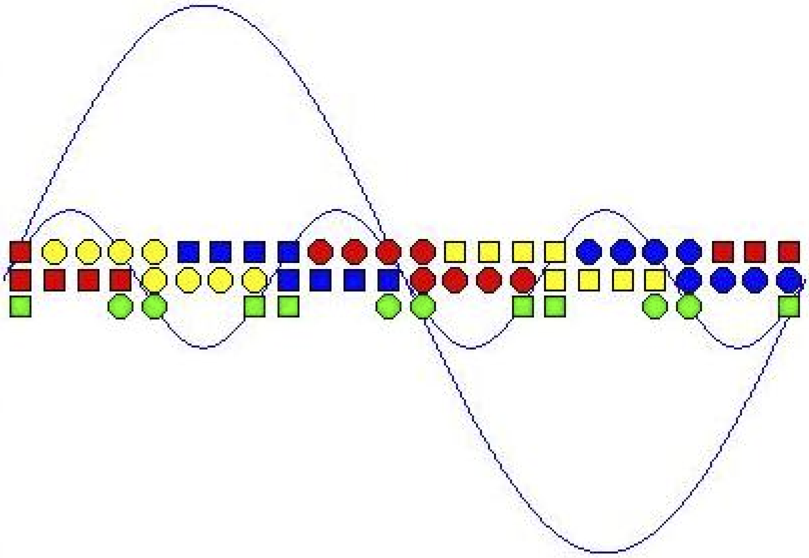

Figure 3.13 Third harmonic winding

The winding factor for the flux fundamental calculated using Equation (3.16) becomes zero. This can also be seen by calculating the total flux through the winding in the area of one pole. The flux is

$$\begin{aligned}\varphi &= \left[\int_0^{W_{\mathrm{H3}}} \sin\left(\pi\frac{x}{\tau_{\mathrm{p}}}\right)dx + \int_{\frac{1}{3}\tau_{\mathrm{p}}+W_{\mathrm{H3}}}^{\frac{1}{3}\tau_{\mathrm{p}}} \sin\left(\pi\frac{x}{\tau_{\mathrm{p}}}\right)dx + \int_{\frac{2}{3}\tau_{\mathrm{p}}}^{\frac{2}{3}\tau_{\mathrm{p}}+W_{\mathrm{H3}}} \sin\left(\pi\frac{x}{\tau_{\mathrm{p}}}\right)dx\right] L'\hat{b}_1 \\ &= -\left(\cos\frac{\pi}{4} - 1 + \cos\frac{\pi}{3} - \cos\frac{7\pi}{12} + \cos\frac{7\pi}{12} - \cos\frac{2\pi}{3}\right)\frac{\tau_{\mathrm{p}}L'}{\pi}\hat{b}_1 = 0.\end{aligned} \qquad (3.53)$$

Thus the flux fundamental does not affect this winding and only the third harmonic can be utilized to obtain the excitation power.

As seen from Table 3.1, the third harmonic flux component in no-load situation is very low since the machine is not saturated and no currents flow in the stator. Since the voltage is induced by the third harmonic according to Equation (3.51), the needed number of turns to induce the sufficient voltage for no-load situation becomes very high. This causes the auxiliary winding to occupy relatively much space in the slot.

In generator short circuit, the third flux density harmonic and thus the voltage induced into the auxiliary winding are nearly six times higher than in no-load operation. This causes the AVR to supply a high amount of power to the field winding and the short-circuit current may rise very high. In this case, it is necessary to use a short-circuit current limiter. Also, the voltage induced into the auxiliary winding must not rise higher than the maximum supply voltage of the automatic voltage regulator.

One advantage of the presented symmetrically wound auxiliary winding is that the waveform of the induced voltage becomes quite sinusoidal. In many automatic voltage regulators, a maximum allowed value to the distortion in the supply voltage is given and this sets requirements for the voltage waveform. A more sinusoidal voltage in the auxiliary winding allows a wider selection of voltage regulators to be used.

Construction 2: Principle of utilizing the fundamental and the third harmonic

Figure 3.14 shows a winding with both H_1 and H_3. Similarly to Construction 1, winding H_3 is used to utilize the third flux density harmonic in generator short circuit. In addition, winding H_1 is added in series to utilize the fundamental in no-load and load operation.

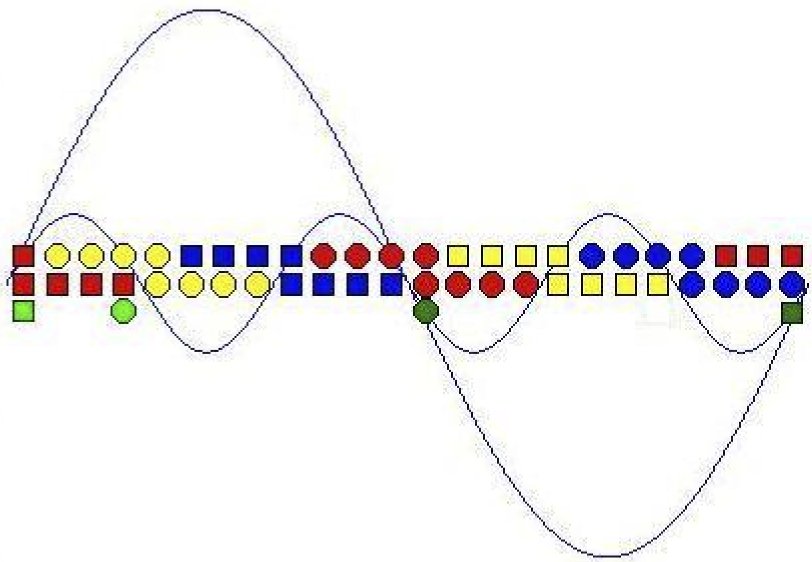

Figure 3.14 Winding with H_3 and full-width H_1

Since also the fundamental is used in the excitation, less turns are needed in winding H_3 and there is necessarily no need to wind the winding symmetrically into the whole stator. Instead, just the needed number of coils can be used. If three coils of H_3 are wound on the area of one pole similar to Construction 1, the fundamental is not induced into the winding. Otherwise, also H_3 can be used to utilize the fundamental.

The winding factor of H_1 for the fundamental is close to one and almost the maximum possible voltage is induced into the coil. However, also the winding factor of H_1 for the third harmonic is close to one and adding H_1 increases the induced voltage in generator short circuit. Thus the attempt to adjust the voltage in no-load and load operation by installing H_1 may cause too high excitation currents in short-circuit operation. A better solution would be to design H_3 only for short-circuit situation and obtain the fundamental voltage using winding that is not affected by the third harmonic [8]. One possibility for this kind of solution is discussed in the following construction.

Construction 3: Separate windings for the fundamental and the third harmonic

In the winding shown in Figure 3.15, the coil pitch of H_1 is reduced to just below two thirds of the pole pitch. Winding H_3 remains similar to the previous solution. Reducing the coil pitch causes the winding factor of H_1 for the third harmonic to be close to zero. The winding factor for the fundamental is still sufficient for effective utilization of the fundamental flux component. Now winding H_3 alone can be designed for the short-circuit excitation and the voltage in no-load and load operation can be adjusted by adding coils H_1 in series without the fear of too high excitation in generator short circuit.

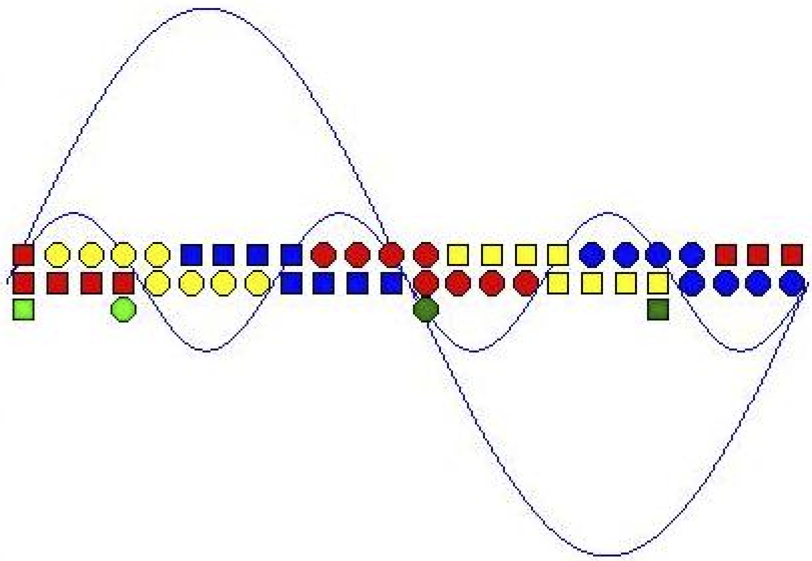

Figure 3.15 Winding with H_3 and narrower H_1

Depending on the voltage induced into H_3 in no-load and load operation, H_1 can be installed in different ways to adjust the voltage induced into the auxiliary winding. If the voltage is too low for overload excitation, H_1 is wound in the same phase as H_3. However, in case the voltage is too high to supply the automatic voltage regulator, it can be lowered by installing H_1 so that a phase shift of 180º occurs between the voltages induced into the windings. Clearly, if H_3 by itself is applicable to supply the voltage regulator in every operating state, H_1 is not needed and the solution remains simpler.

In machines with a fractional-slot main winding, the coil pitches are

$$W_{H1} \approx \frac{2}{3}\tau_p - 1 \tag{3.54}$$

$$W_{H3} \approx \frac{1}{3}\tau_p - 1. \tag{3.55}$$

The coil pitch values can be rounded either up or down to the nearest integer. In case the winding factor remains same in both cases, the smaller value should be used. This is the case with a fractional-slot winding with a pole pitch of

$$\tau_p = k + \frac{1}{2}, k \in \mathrm{N}. \tag{3.56}$$

The final construction of the winding is decided after the needed number of turns in the windings is determined. Since the number of effective auxiliary winding turns per slot is limited, the number of pole pairs and slots per pole in the windings must be varied to have sufficient voltage for excitation. The currents taken by the regulator are relatively low and the number of parallel paths in the winding can remain one.

3.3.6 Voltage waveform simulations

The voltage waveforms for coil H_1 in no load, coil H_3 in short circuit and the presented different winding constructions in both no-load and short-circuit operation were simulated using FCSMEK. Since the induced voltage is proportional to the number of effective turns per slot according to Equations (3.51) and (3.52), only one effective turn was used in the simulations. The simulations were done in the same conditions as in the simulation of the flux density harmonics and using 400 time steps per one period of the terminal voltage. Although slot skewing was used in the example machine, it was not taken into account in the simulations.

H_1 in no load

The no-load waveform for a H_1 coil is presented in Figure 3.16. The voltage consists mostly of the fundamental with a little ripple caused by higher order harmonics.

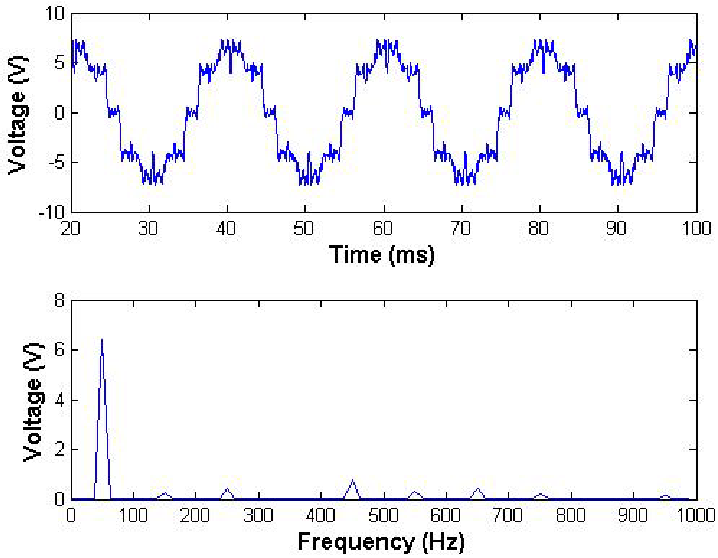

Figure 3.16 H_1, no-load operation

H_3 in short circuit

The short-circuit waveform for a H_3 coil is presented in Figure 3.17. As mentioned earlier, the third harmonic is the dominant component but also some higher order harmonics appear in the voltage spectrum.

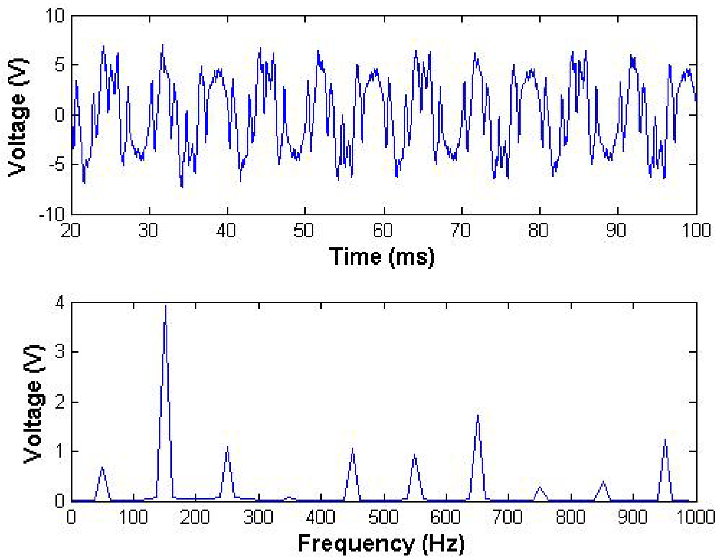

Figure 3.17 H_3, short-circuit operation

Construction 1

The simulation results in no-load and short-circuit operation for the third harmonic winding are presented in Figures 3.18 and 3.19. As can be seen from the no-load simulation, the fundamental is not induced into the winding. Instead, the third harmonic is dominant in both situations. In addition to the third harmonic, the ninth harmonic also has a significant effect on the voltage waveform.

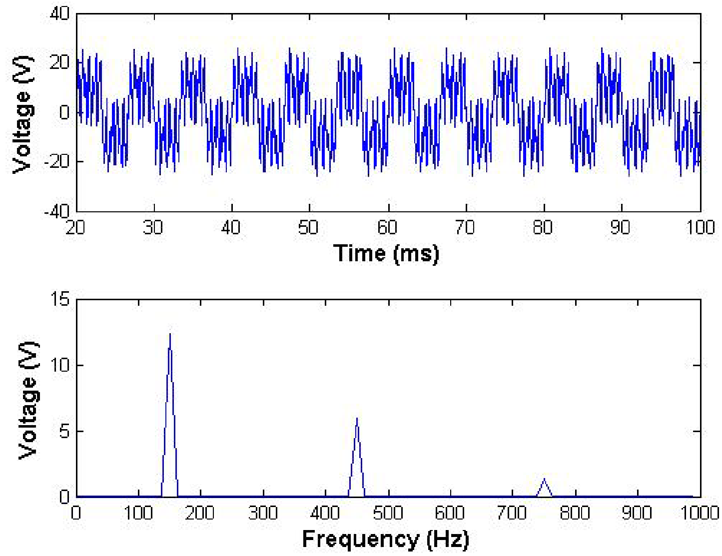

Figure 3.18 Construction 1, no-load operation

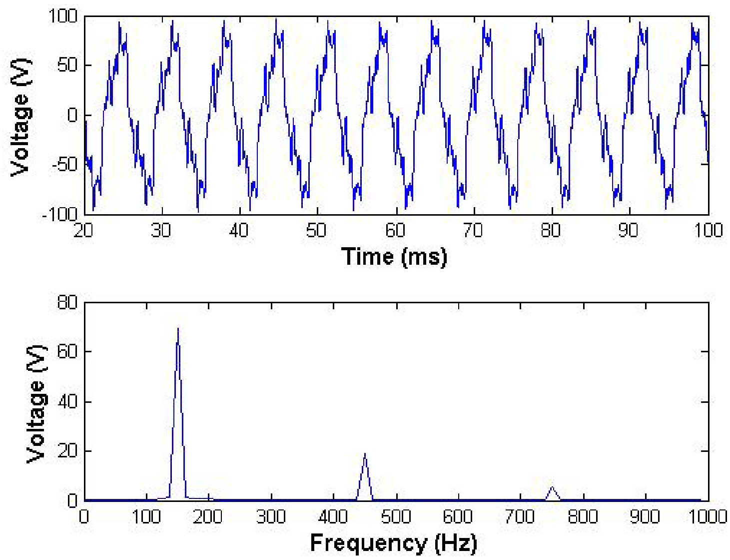

Figure 3.19 Construction 1, short-circuit operation

Construction 2

The simulation results in no-load and short-circuit operation are presented in Figures 3.20 and 3.21. Now the fundamental is the dominant component in no-load operation and produces a relatively high voltage compared to the third-harmonic winding in the previous construction.

In short-circuit operation, the third-harmonic is the dominant component but the distorted waveform also includes several higher order harmonics. The amplitude of the induced voltage is lower than in the previous construction since the total number of turns in the auxiliary winding is lower.

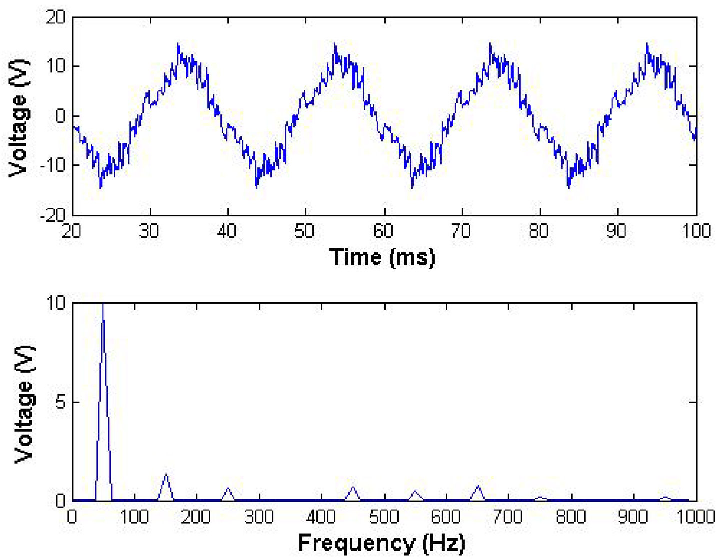

Figure 3.20 Construction 2, no-load operation

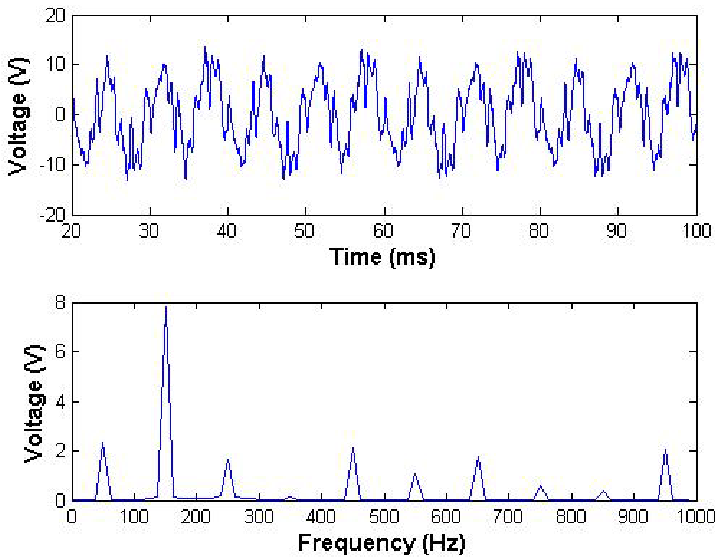

Figure 3.21 Construction 2, short-circuit operation

Construction 3

The simulation results in no-load and short-circuit operation for the winding for both the fundamental and third harmonic are presented in Figures 3.22 and 3.23. Since in this case the coil pitch of H_1 is reduced to two thirds of the pole pitch, the voltage induced by the fundamental is lower in no-load operation. However, the fundamental is still the dominant component in the voltage.

In short-circuit operation, the third harmonic is not induced into winding H_1. Thus the third harmonic component of the total voltage in the auxiliary winding is lower than in the previous construction and the higher order harmonic contents have a greater effect on the voltage waveform. Compared to the short-circuit waveform of a H_3 coil in Figure 3.17, the higher order harmonic contents are greater when H_1 is added in series.

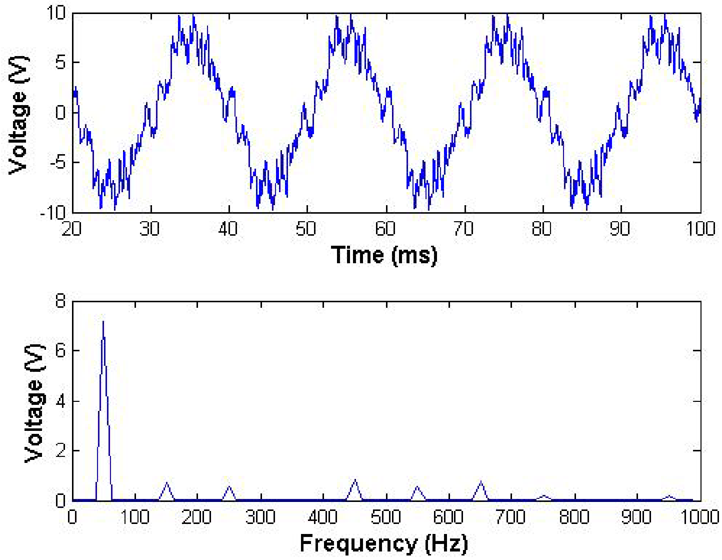

Figure 3.22 Construction 3, no-load operation

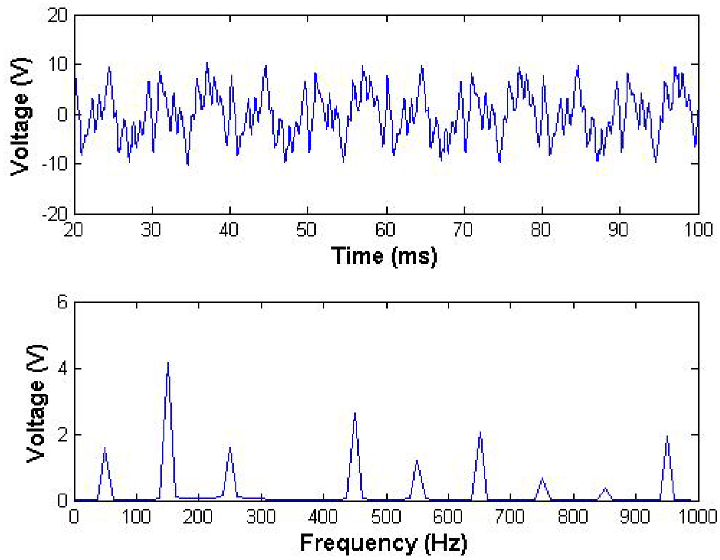

Figure 3.23 Construction 3, short-circuit operation

3.3.7 Existing measurements

Voltage waveform measurements have been done for Constructions 1 and 2. The waveforms are presented in Appendix 2. In the measurement for Construction 1, the auxiliary winding was mounted on a 90 kVA low-voltage synchronous generator similar to the previous example machine and dimensioned so, that the rated voltage is given in no-load operation at the rated speed. This is obtained by using six effective turns per slot. The voltage waveform is first measured in no load, followed by a sudden short circuit. The steady-state short-circuit voltage waveform is obtained after few periods. The results of the measurement are presented in Table 3.2.

Table 3.2 Measured voltages for Construction 1

	No load	Short circuit
Amplitude of voltage (V)	56	555

As can be seen from the amplitude, the voltage induced into the auxiliary winding in generator short circuit is nearly ten times higher than that in no-load operation. This caused a short-circuit current of over five times the rated value which is too high for safe operation. The high voltage may also damage the automatic voltage regulator.

In the measurement for Construction 2, the auxiliary winding consisted of coils of both H_1 and H_3 with three effective turns per slot connected in series and wound into the stator slots of a 2,3 MVA, 660 V, 50 Hz eight-pole synchronous generator. The generator was excited separately and the voltage waveforms were measured in no-load operation with the rated voltage and in generator short circuit with a current of four times the rated current. As can be seen from the results, the no-load and short-circuit voltages consist mostly of the fundamental and the third-harmonic component, respectively. The measured voltages are presented in Table 3.3.

Table 3.3 Measured voltages for Construction 2

	No load	Short circuit
Amplitude of voltage (V)	195	100

3.3.8 Discussion on different winding constructions

All the simulated voltages include a significant amount of higher order harmonics that cause ripple to the voltage waveform. Some of the harmonics in the real machine are eliminated due to slot skewing but can be seen in the simulation in which the skewing is not taken into account. Especially in short-circuit operation, also the calculation method of FCSMEK may not be accurate enough to have a realistic voltage waveform. This is supported by the measured voltage waveforms including less higher order harmonics than the simulated voltages. The waveforms should be measured from the real machine to have reliable results and to make sure that the construction is applicable for excitation.

However, if the fundamental and third harmonic component are considered, the simulations give important information to analyze the applicability of the auxiliary winding construction to excitation. All the presented constructions could be utilized to obtain the excitation power.

The first solution is the most complicated one to manufacture and occupies quite a lot of space in the slot. The possible problems in short-circuit situations would also require deeper analysis to guarantee safe operation. The measurements proved that the voltage in short-circuit operation is dangerously high. The short-circuit voltage was nearly 70 % higher than predicted by the simulations. The second solution also encounters similar problems in short-circuit situation.

The last construction with a minimum possible number of coils is simple to manufacture and thus a good solution to supply the excitation power to a low-voltage synchronous generator. The windings for the fundamental and third harmonic can be designed separately to meet the excitation demand in different situations. However, since the winding is not symmetrically wound into the whole stator, the relatively high distortion in the voltage waveform must be taken into account when selecting the automatic voltage regulator.

3.3.9 Design considerations

Of all other excitation methods, an auxiliary winding is the simplest solution to supply the automatic voltage regulator and is used as the primary excitation method in low-voltage synchronous generators under consideration. It reduces the complexity of the regulator plate and increases the reliability of the system. Since no external devices outside the machine are needed, the length of the machine is also reduced and more space is left in the terminal box. The customer interface remains similar to other excitation solutions.

To ensure that the voltage of the auxiliary winding will be on the needed level for both the short-circuit and overload situations, separate windings for adjustment can be installed in addition to the calculated primary winding. The adjustment winding can consist of few coils of both H_1 and H_3 that can be connected in series with the original auxiliary winding if the measured voltage levels in short-circuit or load operation differ from the needed values.

The most significant drawback in the use of the auxiliary winding is that a damaged winding cannot be repaired or replaced after the impregnation. A defected winding may also cause damage to the main winding or the stator core. This increases the challenge in the winding process. One possibility to increase the reliability and ease the after-sales work is to install a spare winding that can be taken in use in case the primary winding is damaged.

A slot asymmetry occurs between the slots with and without the auxiliary winding. Since the filling factor is higher in the slots with the auxiliary winding, no temperature control elements should be installed in these slots. If the space needed by the auxiliary winding is left empty in all the other slots, the generator capacity decreases.

3.4 Excitation power with PMG

In PMG excitation, a separate permanent magnet generator is used to supply the excitation power to the automatic voltage regulator. A permanent magnet rotor is installed on the shaft of the main machine, and the AVR is supplied by the three-phase voltage on the stator side of the PMG. When PMG excitation is used, self-excitation is automatically enabled and no permanent magnet poles are needed in the exciter stator. Figure 3.24 shows a schematic of supplying the voltage regulator with a PMG.

The PMG is capable of supplying the excitation power in both normal operation and in generator short circuit. The AVR supply voltage is independent of the main excitation and depends only on the regulator input current.

In low-voltage synchronous generators, PMG excitation is available as an option to the auxiliary winding. Compared to the auxiliary winding, the excitation implemented with PMG is a more expensive and more complicated solution. The permanent magnet rotor also increases the axial length of the machine.

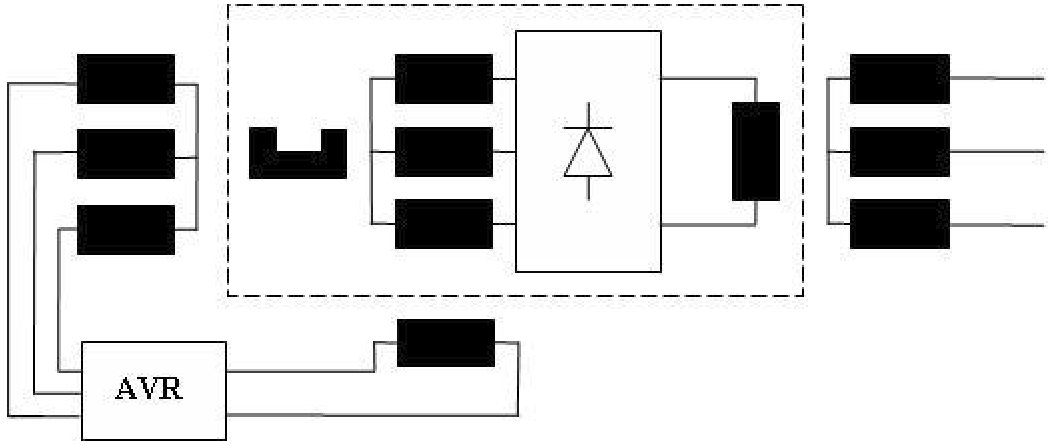

Figure 3.24 Excitation power supply with PMG

4 Excitation requirements

4.1 Overview

In the design of marine low-voltage synchronous generators, IEC standards 60034-1 for rating and performance of rotating electrical machines and 60092 for electrical installations in ships must be taken into account. The requirements in IEC 60092 are met by the criteria set by the marine classification societies and are discussed in context of them. Considering the excitation, the most important requirements of IEC 60034-1 include limits for the total harmonic distortion (THD) [9] and the EMC requirements.

The classification societies establish and apply technical requirements for the design, construction and survey of marine related facilities [10]. These requirements are published as classification rules and are developed to contribute to the structural strength of the ship and the reliability of e.g. the propulsion and power generation systems for the purpose of safe operation of the ship.

Based on standard IEC 60092, the requirements set by DNV cover the most criteria set by the other IACS members. Considering the excitation, the most important requirements deal with voltage regulation in both steady state and transient operation and parallel operation of generators [11].

4.2 Standards

4.2.1 Total harmonic distortion

The total harmonic distortion is measured from the line-to-line terminal voltage either one harmonic at a time or directly by means of a meter specially designed for the purpose. By the definition, THD covers frequencies up to the 100th harmonic and is given by

$$THD = \sqrt{\sum_{h=2}^{100} u_h^2}\ , \tag{4.1}$$

where

$$u_h = \frac{U_h}{U_1} \tag{4.2}$$

is the ratio between the amplitude of voltage harmonic *h* and the amplitude of the fundamental voltage component. The maximum values for the THD and a single harmonic are 5 % and 3 %, respectively.

4.2.2 Electromagnetic compatibility

Rotating electrical machines with rated voltage not more than 1000 VAC must fulfil the EMC requirements defined in IEC standard 60034-1, Chapter 13. The electronic components mounted inside the machine and which are essential for its operation, such as rotating excitation devices, are considered as part of the machine and covered by the standard. Requirements applying to the final drive system and its components are outside the scope of the standard.

The radiated and conducted emissions from rotating electrical machines are tested in accordance and must comply with the requirements set by the Special International Committee in Radio Interference (CISPR). The limits for radiated and conducted emissions are presented in Table 4.1.

Table 4.1 CISPR limits for radiated and conducted emissions

	Frequency range (MHz)	Limits
Radiated emission	30 to 230	30 dB(μV/m)
	230 to 1000	37 dB(μV/m)
Conducted emission on AC supply terminals	0,15 to 0,50	66 to 56 dB(μV) 56 to 46 dB(μV) average
	0,50 to 5	56 dB(μV) 46 dB(μV) average
	5 to 30	60 dB(μV) 50 dB(μV) average

The radiated emissions are measured at a 10 m distance or alternatively from a 3 m distance using limits 10 dB higher than the given values. In the frequency range from 0,15 to 0,50 MHz, the conducted emission limits decrease exponentially between the given values. Except for the average values, all the given limits are quasi-peak values.

4.3 Classification

4.3.1 Voltage regulation

In steady state, the AVR must be able to keep the voltage within ±2,5 % of the rated voltage under all steady load conditions. The limit can be increased to ±3,5 % for emergency generator sets.

When specifying the requirements for voltage regulation in load changes, a definition of sudden load is used. The sudden load is defined to be more than 60 % of the full load current at power factor of 0,4 lagging or less. When switching on the sudden load, the instantaneous voltage drop must not exceed 15 % of the rated voltage. When the load is switched off, the voltage rise must not exceed 20 %. In both cases, the voltage regulation must restore the voltage within ±3 % of the rated voltage within 1,5 s. For emergency generator sets not in parallel operation, the limits can be increased to ±4 % and 5 s.

4.3.2 Parallel operation

The sharing of active and reactive power must be stable under all load conditions. The oscillations must be within ±20 % of the rated current. In the range of 20 to 100 % of the rated reactive load of each generator, the generator's actual reactive load must not differ from its proportionate share of the total reactive load by more than 10 % of the rated reactive load of the largest generator or by more than 25 % of the rated reactive load of the smallest generator in parallel. If oscillations occur, the actual reactive load is the mean value of the generator's reactive load.

4.3.3 Other requirements

The generator must withstand an overload current equal to 1,5 times the rated current for at least 30 s. Under steady short-circuit conditions, the generator must be capable of withstanding a current of at least three times the rated full load current for at least 2 s without sustaining any damage. This is necessary for the circuit-breaker to be able to operate and separate the generator from the network.

Generators over 1500 kVA must be prepared for external signal for initiation of de-excitation.

5 Synchronous generator design

5.1 Overview

Synchronous generators are designed to match the customers' needs. They are typically tailor-made for certain applications which increases the challenge and need for computation in the machine design. The design process starts after a customer sends an inquiry for a generator of a certain type for a certain application. For several applications, an offer can be made using an applicable machine type from a list of ready-calculated machines. Usually, however, the inquired machine differs noticeably from the listed machines and must be dimensioned by an electrical designer.

5.2 Existing design software

5.2.1 Analytic dimensioning programs

In synchronous machine calculation, several analytical calculation programs are used. Program THW32 is used as a user interface in which the parameters of the machine in calculation are defined. Sub-programs can be called from THW32 and used for different calculation tasks with the defined machine parameters. The most important sub-programs are S143 and A045 for the calculation of main parameters and performance of the main and exciter machines, respectively, and S125 for thermal calculations. S143 executes the electrical calculations for salient-pole synchronous machines when the machine geometry is known. A045 executes the calculations for a DC-AC exciter machine and calculates the needed field voltage and current in the no-load and short-circuit operation and in the load conditions defined by the user.

5.2.2 Offer calculation programs

Offer calculation programs are used as sales support tools to automate the dimensioning and pricing of a machine and therefore to speed up the inquiry-offer process. Using customer requirements as initial data, they automatically select an applicable pre-calculated machine from a list or calculate an optimal machine using dimensioning programs. An offer of a machine is generated automatically with no need for manual calculation or design.

Nestori is an offer calculation program for synchronous machines developed since the mid 1990's. It uses THW32 in automated machine design and optimization. Originally designed purely as an offer process tool for sales personnel, Nestori is now used throughout the delivery process to manage the machine configuration.

Bemari is an offer calculation program based on list machines. Implemented in Microsoft Excel, Bemari is used by the sales personnel of the Marine Systems business unit to produce budget offers on ship electric and propulsion systems. Machine selection from the standard machine solution database is performed using macros and programmed logic. As output, the technical specifications and price of the machine are obtained. Bemari can be used as a part of a program that calculates an offer of the electric system of a whole ship.

5.2.3 Numerical calculation programs

Numerical methods must be used when more accurate models of machines are needed or more complex problems need to be solved. They are used in machine design e.g. in more detailed calculation of losses as well as in transient and flux harmonic analysis of the machines.

Finite element method (FEM) is a commonly used numerical method in electrical machine design [12]. The basic idea of the method is to solve a partial differential field equation by dividing the examined area, e.g. the cross-section of a machine, into small sub-areas a.k.a. elements in which the field in calculation is represented by a function, usually a polynomial with unknown coefficients. Using the polynomials, the field values in an element are interpolated between the element node values. Choosing minimization of the field energy as a variation principle, the coefficients of the functions in the elements can be solved.

FCSMEK is a FEM calculation program developed in the Laboratory of Electromechanics in Helsinki University of Technology. The program divides the smallest possible symmetrical part of a cross-section of an electrical machine into elements and solves the magnetic vector potential in the section. The magnetic field is modeled in two dimensions. Depending on the needed accuracy, the used elements can be either of first, second or third order. The calculation time depends strongly on the order of the elements.

5.3 Base machine method

5.3.1 Design parameters

From the inquiry, the initial parameters for the machine design are defined. These parameters include the rated output power and power factor, rated voltage, rated frequency and pole-pair number. Other data that must be considered to optimize the machine in both technical and commercial points of view include the standards and classification, temperature rise class, cooling method, enclosure class, excitation method and overload requirements.

Dimensioning of a rotating electrical machine is a challenging task in which 30 to 40 different variables must be considered. These variables include the inner diameter and the length of the stator, stator slot number, stator winding construction, pole dimensions and field winding construction [13].

5.3.2 Dimensioning

Using the initial data, an applicable base machine is selected. The base machine is usually a previously manufactured generator that is used as a starting point for the dimensioning. The inquired generator is dimensioned by modifying the variable parameters until the requirements of the inquiry are met. In most cases, only the length and the windings of the machine have to be changed and the design process remains relatively simple as the cross-section of the machine is constant.

In the design, certain limits for the magnetic flux density and current density are taken into account. The limits depend on the application, ambient environment and customer specifications.

6 Excitation design

6.1 Selected auxiliary winding construction

From the three different auxiliary winding constructions studied in Chapter 3.3, Construction 3 was selected to be used in low-voltage synchronous generator excitation. The main reasons for selecting Construction 3 were the simplicity of the winding construction and the possibility to design windings H_1 and H_3 separately for load and short-circuit operation. In the following, the dimensioning process for the selected auxiliary winding solution is presented and requirements and design of the auxiliary-winding supplied automatic voltage regulator system are discussed.

6.2 Initial data

As initial data for the design, the basic main machine data and excitation data are needed. In addition, certain user defined data for changeable design parameters must be known. The needed main machine data includes the rated voltage, frequency, slot number, slot dimensions and dimensions of the main winding.

The excitation data includes the values for the field voltage U_{m} and current I_{m} of the excitation machine in different operating points. The data is needed at the rated load, overload and short-circuit operation. The maximum needed values of the field voltage and current for both overload and short-circuit situations are used to determine the minimum supply voltage for the automatic voltage regulator. These maximum values are denoted by $U_{\mathrm{m,max,N}}$ and $I_{\mathrm{m,max,N}}$ for the rated load, $U_{\mathrm{m,max,ol}}$ and $I_{\mathrm{m,max,ol}}$ for overload and $U_{\mathrm{m,max,k}}$ and $I_{\mathrm{m,max,k}}$ for short circuit.

The user defined data includes variable parameters needed for the design. The maximum current densities in the auxiliary winding are defined separately for the rated load, overload and short-circuit situations. They are denoted by $J_{\mathrm{a,max,N}}$, $J_{\mathrm{a,max,ol}}$ and $J_{\mathrm{a,max,k}}$. To guarantee the processibility of the winding, the maximum allowed value for the main winding filling factor must be set. It is denoted by η_{max}. The filling factor for the auxiliary winding is denoted by η_{a}. The insulation thicknesses and wire diameters that are used for the auxiliary winding must also be known in the design.

The maximum values for the numbers of slots per pole in windings H_1 and H_3 can be defined by the user but are clearly limited to values

$$q_{\mathrm{H1,max}} = W_{\mathrm{H1}} \tag{6.1}$$

and

$$q_{\mathrm{H3,max}} = W_{\mathrm{H3}}\,. \tag{6.2}$$

The third harmonic flux density component in generator short circuit is needed to design the auxiliary winding for the short-circuit excitation. More accurate flux-density harmonic analysis might provide a working analytical model to calculate the amplitude of the needed component using other machine parameters. Since the model presented in Subsection 3.3.3 is not detailed enough to have an analytical value, the flux density harmonics can be calculated using FCSMEK.

6.3 Dimensioning of auxiliary winding

6.3.1 Ceiling values

The maximum values for the excitation current and voltage that much be reached in a certain operating point are called ceiling values. The ceiling values are defined from the maximum values using safety factors k_s and k_{sk} for load operation and short-circuit operation, respectively, to have a margin to guarantee the sufficiency of the excitation. Typically, the values for the safety factors are around 1,05. The ceiling values are

$$\begin{cases} \hat{U}_{m,N} = k_s U_{m,max,N} \\ \hat{I}_{m,N} = k_s I_{m,max,N} \end{cases} \tag{6.3}$$

for the rated load,

$$\begin{cases} \hat{U}_{m,ol} = k_s U_{m,max,ol} \\ \hat{I}_{m,ol} = k_s I_{m,max,ol} \end{cases} \tag{6.4}$$

for overload and

$$\begin{cases} \hat{U}_{m,k} = k_{sk} U_{m,max,k} \\ \hat{I}_{m,k} = k_{sk} I_{m,max,k} \end{cases} \tag{6.5}$$

for short-circuit operation.

6.3.2 Space for auxiliary winding

For the dimensioning, it is important to know the maximum possible number of turns in the auxiliary winding that can be wound into one slot. To calculate the maximum value, the needed cross-sectional area of the wire used in the auxiliary winding must be known. In the following, the needed wire diameter and maximum number of turns are calculated.

Since the supply voltage is rectified into DC in the AVR using a full-wave diode bridge, the excitation current is the same as the rms current in the auxiliary winding:

$$I_a = I_m . \tag{6.6}$$

The needed cross-sectional copper area of the auxiliary winding is obtained using the maximum current densities:

$$A_{Cu,a} = \max\left\{ \frac{\hat{I}_{m,N}}{J_{a,max,N}}, \frac{\hat{I}_{m,ol}}{J_{a,max,ol}}, \frac{\hat{I}_{m,k}}{J_{a,max,k}} \right\} . \tag{6.7}$$

Due to small currents, only one conductor is used in the auxiliary winding and the closest corresponding wire diameter is selected. The total cross-sectional area of the auxiliary winding with insulation is denoted by $A_{i,a}$.

The slot is filled by the main winding, slot insulation, layer insulation and auxiliary winding. The areas of the main winding and insulation are denoted by jA_i and A_ins, respectively. The area left for the auxiliary winding is obtained as the difference of the slot area and the sum of the areas of the main winding and insulation. Thus the maximum number of auxiliary winding turns per slot is given by

$$j_\mathrm{max,a} = \frac{\eta_\mathrm{a}}{A_\mathrm{i,a}}\left(A_\mathrm{slot} - A_\mathrm{ins} - \frac{jA_\mathrm{i}}{\eta_\mathrm{max}}\right). \qquad (6.8)$$

6.3.3 Dimensioning H_3

Winding H_3 is dimensioned to satisfy the excitation demand in generator short circuit. The minimum voltage in the auxiliary winding to reach the ceiling value for short circuit is given by Equation (3.11) and is

$$U_\mathrm{a,min,k} = \frac{\pi}{2\sqrt{2}}\hat{U}_\mathrm{m,k}\,. \qquad (6.9)$$

Since this voltage is induced by the third harmonic flux component according to Equation (3.51), the needed number of turns in H_3 is given by

$$N_\mathrm{H3} = \frac{\pi}{3\sqrt{2}}\frac{U_\mathrm{a,min,k}}{\omega\xi_\mathrm{H3,3}\tau_\mathrm{p}L'\hat{b}_3}\,. \qquad (6.10)$$

The number of parallel paths in the auxiliary winding is assumed to be one and thus the number of turns is given by

$$N_\mathrm{H3} = p_\mathrm{H3}q_\mathrm{H3}j_\mathrm{H3}\,. \qquad (6.11)$$

Since the maximum number of turns per slot is known, the condition for the design of H_3 is

$$j_\mathrm{H3} = \frac{N_\mathrm{H3}}{p_\mathrm{H3}q_\mathrm{H3}} \leq j_\mathrm{max,a}\,. \qquad (6.12)$$

Using Equation (6.12), the needed number of pole pairs p_H3 and slots per pole q_H3 can be defined to have a sufficient number of turns per slot. Initially, values $p_\mathrm{H3} = q_\mathrm{H3} = 1$ can be used. When the number of slots per pole is changed, the winding factor changes and thus a new value for the number of total turns must be calculated.

6.3.4 Construction of H_3

After the needed pole-pair number of winding H_3 is obtained, the winding construction needs to be decided. The possible constructions depend on the number of slots per pole in the winding. If the number of slots per pole is one, the coils are placed next to each other so that three coils can be wound in the area of one pole. This saves space for the spare winding and the adjustment windings. Figure 6.1 shows an example of winding H_3 with pole-pair number of four and one slot per pole.

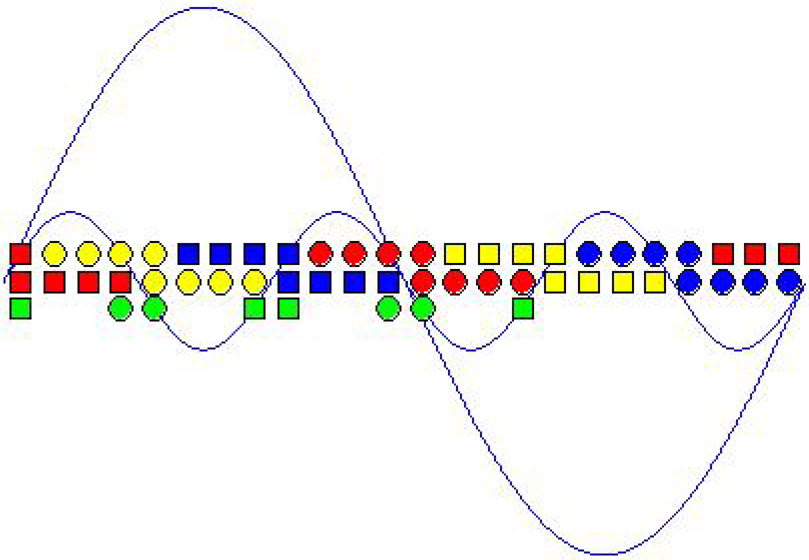

Figure 6.1 Winding H_3 with one slot per pole

If the number of slots per pole in the winding is greater than one, three coils cannot be wound in the area of one pole, but instead on the area of one pole pair. Figure 6.2 shows an example of winding H_3 with two slots per pole.

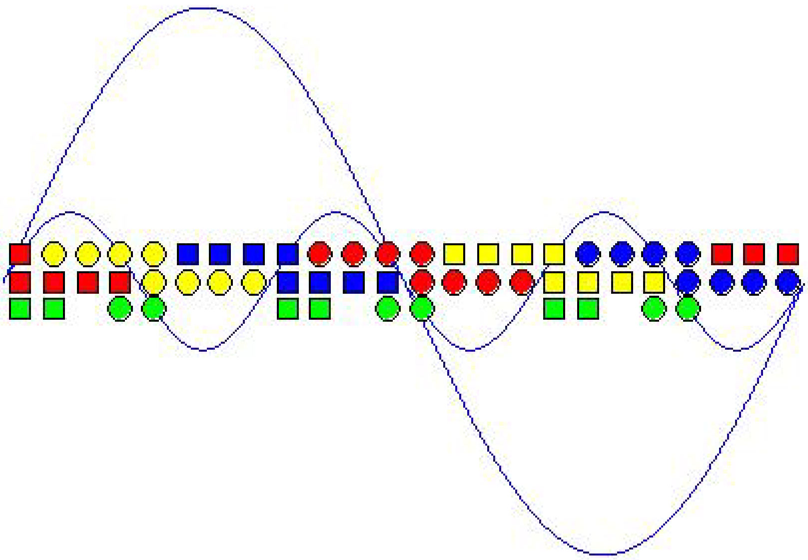

Figure 6.2 Winding H_3 with two slots per pole

In both cases, the effect of the fundamental flux-density component on every group of three coils is neglected and thus only windings with the pole-pair number differing from any multiple of three produce a voltage in no-load and load operation.

6.3.5 Dimensioning H_1

After the short-circuit requirements are satisfied, the voltage of the auxiliary winding in load operation must be set to a sufficient level to supply the automatic voltage regulator. If the voltage of winding H_3 in load operation is either too low to meet the demand for overload or too high for to safely supply the regulator, winding H_1 must be used in addition to adjust the voltage to a correct level.

The voltage in load operation must be at least

$$U_{\mathrm{a,min,ol}} = \frac{\pi}{2\sqrt{2}}\hat{U}_{\mathrm{m,ol}}\,. \tag{6.13}$$

In case the voltage of H_3 in load operation is too low for the overload situation, winding H_1 must be used to raise the voltage. Since the windings are connected in phase and the voltage in both windings is induced by the fundamental, the total rms voltage induced into the auxiliary winding is obtained as the sum of the rms voltages in both H_3 and H_1. The induced voltages are proportional to the main voltage and given by

$$U_{\mathrm{H3}} = \frac{N_{\mathrm{H3}}}{N}\frac{\xi_{\mathrm{H3,1}}}{\xi_1}\frac{U_{\mathrm{N}}}{\sqrt{3}} \tag{6.14}$$

and

$$U_{\mathrm{H1}} = \frac{N_{\mathrm{H1}}}{N}\frac{\xi_{\mathrm{H1,1}}}{\xi_1}\frac{U_{\mathrm{N}}}{\sqrt{3}}\,. \tag{6.15}$$

Since H_3 is already defined, the needed number of turns in H_1 is given by

$$U_{\mathrm{H3}} + U_{\mathrm{H1}} = U_{\mathrm{a,min,ol}} \tag{6.16}$$

$$\Rightarrow \left(N_{\mathrm{H1}}\xi_{\mathrm{H1,1}} + N_{\mathrm{H3}}\xi_{\mathrm{H3,1}}\right)\frac{1}{\sqrt{3}}\frac{U_{\mathrm{N}}}{N\xi_1} = U_{\mathrm{a,min,ol}} \tag{6.17}$$

$$\Rightarrow N_{\mathrm{H1}} = \frac{1}{\xi_{\mathrm{H1,1}}}\left(\sqrt{3}N\xi_1\frac{U_{\mathrm{a,min,ol}}}{U_{\mathrm{N}}} - N_{\mathrm{H3}}\xi_{\mathrm{H3,1}}\right). \tag{6.18}$$

In case the voltage of H_3 is higher than the maximum supply voltage $U_{\mathrm{AVR,max}}$ of the automatic voltage regulator, winding H_1 must be used to lower the voltage. H_1 is connected so that a phase shift of 180º occurs between the voltages induced into the windings. Thus the total rms voltage of the auxiliary winding is obtained as the difference of the rms voltages in H_3 and H_1. Similarly to Equations (6.16) – (6.18), the needed number of turns in H_1 is given by

$$U_{\mathrm{H3}} - U_{\mathrm{H1}} = U_{\mathrm{AVR,max}} \tag{6.19}$$

$$\Rightarrow \left(N_{\mathrm{H1}}\xi_{\mathrm{H1,1}} - N_{\mathrm{H3}}\xi_{\mathrm{H3,1}}\right)\frac{1}{\sqrt{3}}\frac{U_{\mathrm{N}}}{N\xi_1} = U_{\mathrm{AVR,max}} \tag{6.20}$$

$$\Rightarrow N_{\mathrm{H1}} = \frac{1}{\xi_{\mathrm{H1,1}}}\left(\sqrt{3}N\xi_1\frac{U_{\mathrm{AVR,max}}}{U_{\mathrm{N}}} + N_{\mathrm{H3}}\xi_{\mathrm{H3,1}}\right). \tag{6.21}$$

As in case of H_3, the pole-pair number and the number of slots per pole can be defined using equation

$$j_{\mathrm{H1}} = \frac{N_{\mathrm{H1}}}{p_{\mathrm{H1}} q_{\mathrm{H1}}} \leq j_{\mathrm{max,a}} . \tag{6.22}$$

6.3.6 Construction of H_1

Similarly to H_3, the construction of H_1 depends on the number of slots per pole but also on the construction of H_3. The phase angle of the voltage induced into H_3 in load operation depends on the pole-pair number and must be taken into account when connecting H_1 in series.

Equations (6.16) and (6.19) only give the right result when winding H_1 is connected in phase with H_3. However, calculating analytically the correct way to connect H_1 and H_3 in phase is quite complicated and the resulting winding construction may occupy more space in the stator than a simpler optimized solution. Thus H_1 is never connected in the middle of a pole but started from either side of the pole and connected as close to H_3 as possible. Figures 6.3 and 6.4 present examples of connecting H_1 and H_3.

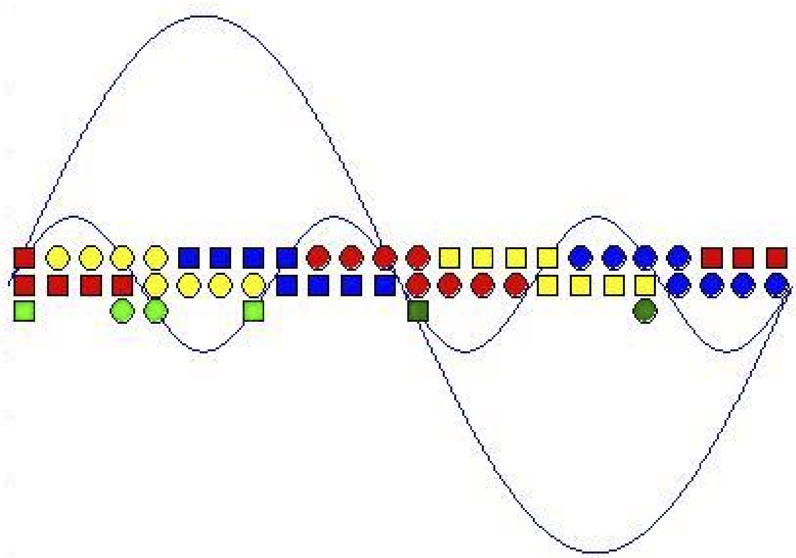

Figure 6.3 Connecting windings H_3 and H_1 when H_3 has two pole pairs

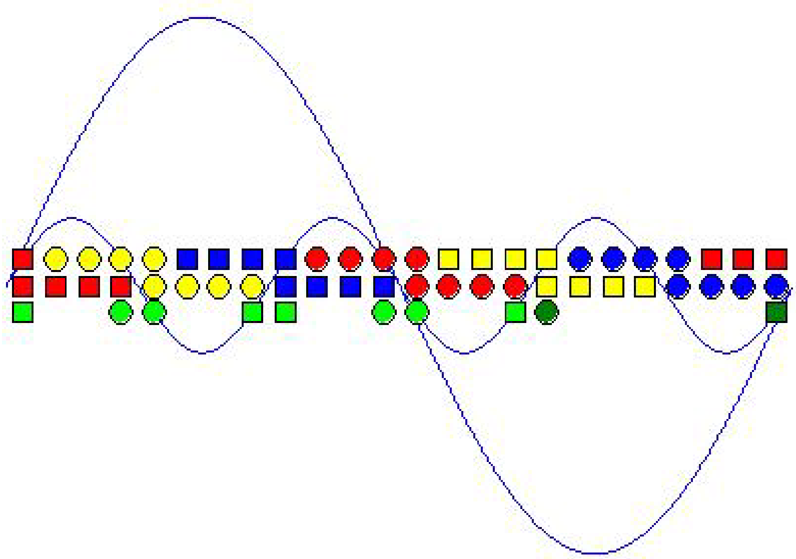

Figure 6.4 Connecting windings H_3 and H_1 when H_3 has four pole pairs

Since H_1 and H_3 are not exactly in the same phase, Equations (6.16) and (6.19) do not give an exact value for the voltage induced into the auxiliary winding. However, the sufficiency of the voltage in both load and short-circuit operation can be verified by deriving the total winding factors of the final construction for both the fundamental and third harmonic using Equation (3.16) and calculating the induced voltage with Equation (3.51).

Equation (6.1) presented the absolute maximum value for the number of slots per pole in H_1. However, to save space for the spare winding and the measurement windings, one coil group of H_1 should be able to fit on the area of only one pole. To achieve this, the maximum number of slots per pole should be

$$q_{\mathrm{H1,max}} = \tau_{\mathrm{p}} - W_{\mathrm{H1}} . \tag{6.23}$$

6.4 Automatic voltage regulator system design

6.4.1 Regulator solutions

For low-voltage synchronous generators, two different automatic voltage-regulator solutions can be chosen by the customer depending on the requirements set for the excitation system. The first solution includes a simple analog regulator covering the minimum requirements needed for the generator voltage regulation. Another more versatile solution is implemented with a digital voltage regulator and may include more complex control functions in addition to the minimum requirements. The selection is based on the requirements set by the customer.

6.4.2 Limits for output

Clearly, the automatic voltage regulator should be able to meet the excitation demand of the excitation machine. Typically, the manufacturers provide values for the maximum continuous excitation current and voltage and also values for a short-time overload situation. The regulator must be selected so that the field current and voltage needed by the excitation machine in different situations fit in the range for the output values.

6.4.3 The control system

When supplied from an auxiliary winding utilizing the fundamental and third harmonic flux component, the first requirement for the automatic voltage regulator is the possibility to supply it with voltages of two different frequencies. This is difficult to implement in regulators using silicon-controlled rectifiers to control the field voltage since the firing frequency of the thyristors must also be tripled in case of short circuit. Chopper-type regulators with diode rectifiers are a better solution to be utilized together with the selected auxiliary winding construction.

Another factor that may prevent the usage of thyristor bridges is the distorted voltage waveform that occurs if the selected auxiliary winding solution is used. In case the harmonic contents cause the voltage to drop below zero before the actual voltage component utilized to supply the regulator, the thyristors are turned off and will not conduct the current until the next firing signal. Since the firing of the thyristors depends on the fundamental, the average voltage supplied to the AVR is reduced and the regulator cannot produce sufficient field voltage to the exciter.

6.4.4 The regulator system

The automatic voltage regulator system depends on the selected regulator solution. The regulator is mounted on a separate mounting plate and placed inside the main terminal box of the machine. Some digital regulators with a control panel user interface may be installed outside the machine.

In low-voltage synchronous generators, the main voltage value needed by the automatic voltage regulator can usually be measured directly from the main terminals of the generator. If the voltage regulator is requested to be galvanically separated from the terminals, a voltage transformer can be used. The phase current measurement is taken from the middle phase using a current transformer.

Since the auxiliary winding is dimensioned to produce a short-circuit current of three times the rated current, no excitation current limiter is required for the generator short-circuit situation. Thus the minimum components on the regulator plate only include the automatic voltage regulator and a circuit breaker for de-excitation. Some optional control functions, as excitation current measurement and overvoltage protection, may require installation of additional components. Figure 6.5 shows an example of a minimum automatic voltage regulator system.

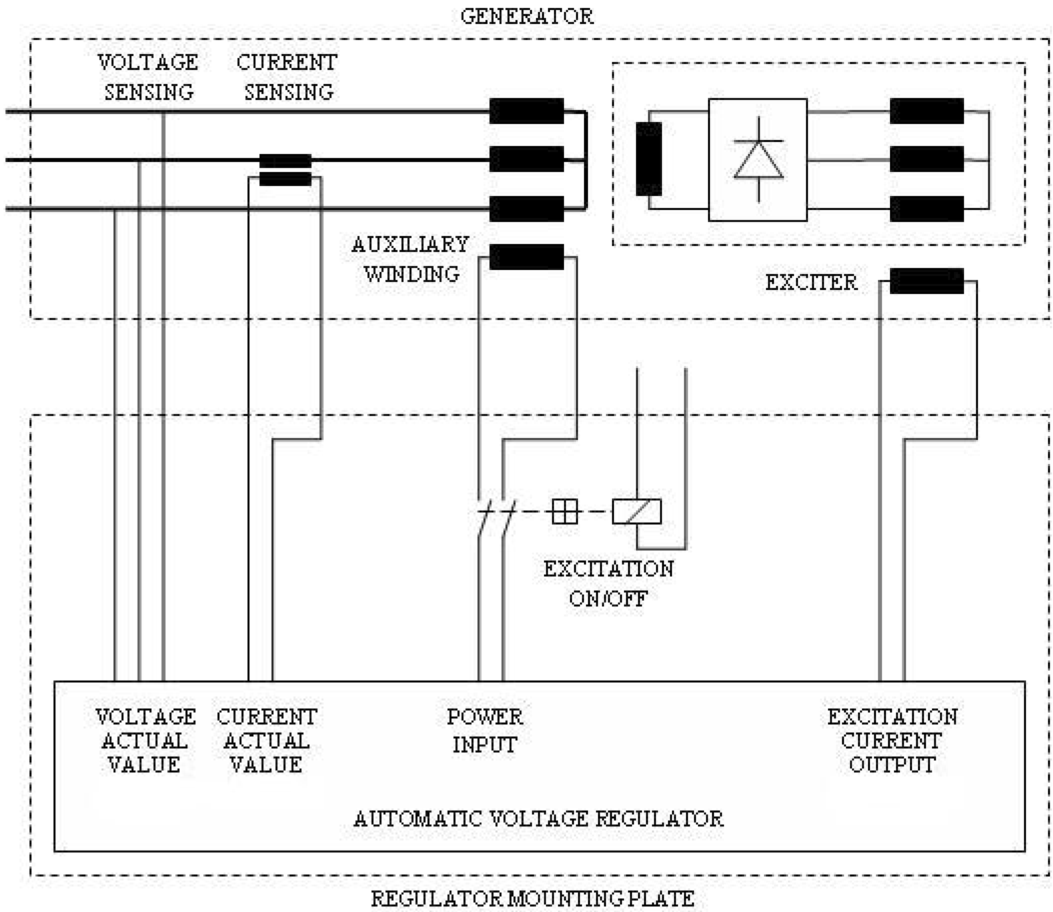

Figure 6.5 Minimum automatic voltage regulator system

6.5 Design program

6.5.1 Implementation

The auxiliary winding design was implemented with MATLAB. The data for the main machine is given by program S143 and the excitation demand in different operating states is given by program A045. In addition, user defined data including changeable parameters such as maximum values for the current densities and filling factors and safety margins for ceiling excitation are read as an input. The data is read by the program from an ASCII text file containing the needed parameters in pre-defined order.

The program solves the equations in Section 6.3 and as output, the construction and winding diagram for the auxiliary winding are written in separate text files. In Appendix 3, the calculation diagram used in the dimensioning of the auxiliary winding is presented. Appendix 4 gives an example of the program output files.

6.5.2 User interface

The MATLAB code was compiled into a binary file and a simpler user interface for the program was implemented with Microsoft Excel. The initial values can be filled into an Excel workbook from which the program can also be run. The output files are opened into a separate workbook.

Using Microsoft Excel allows relatively simple interfaces to existing dimensioning programs. In the future, the initial machine and excitation data can be imported directly from S143 and A045 by running the design program from THW. This allows simpler and more effective use of the program. One important addition to the program would also be to combine the calculation of the third flux-density harmonic needed in dimensioning of the auxiliary winding for the short-circuit situation. Another possibility to simplify the design is to tabulate calculated flux-density values for certain base machines and to search a suitable value automatically for the machine for which the auxiliary winding is dimensioned.

6.5.3 Verification

Verification of valid operation of the design program would have to be done by measurements. A low-voltage synchronous generator utilizing the selected auxiliary winding solution could not be made during this work and proper measurements to validate the analytical dimensioning model could not be performed. However, the existing measurements of the voltage waveforms in no-load and short-circuit operation can be used to analyze the operation. In the following, the measurement of the waveforms in Construction 1 is compared to the FEM simulations, the measurement of the waveforms in Construction 2 is compared to the analytical dimensioning model and the simulations of Construction 3 are compared to the analytical model.

Construction 1

The simulations in subsection 3.3.6 were done using one effective turn per slot, and the auxiliary winding of the machine used in the simulations had six effective turns per slot. Thus the voltage induced into the auxiliary winding should be six times higher than in the simulation results. In no-load operation, the amplitude of the simulated voltage was 12 V and the measured amplitude was 56 V. The ratio of the values is 4,7 which is quite close to six.

Since the measured short-circuit current was five times the rated value, the short-circuit simulation was repeated with the same current to compare the results. However, the amplitude of the third harmonic voltage component remained the same as in the previous simulation. This may be caused by saturation of the machine. The simulated amplitude was 70 V and the measured amplitude was 557 V. The ratio of the amplitudes is 8,0 and differs more from the theoretical value than in case of no-load operation.

Construction 2

In no-load operation, the voltage induced into the auxiliary winding should be obtained as the sum of the voltages in Equations (6.14) and (6.15) if the windings were connected in phase. The 660 V generator used in the measurement had 11 turns per phase and a winding factor of 0,915 for the fundamental. The winding factors of the fundamental for windings H_1 and H_3 were 1,000 and 0,500, respectively, and both windings had three effective turns per slot. Thus the analytical value for the amplitude of the voltage induced into the auxiliary winding is 241 V. The difference between the analytical value and the measured amplitude of 195 V is relatively big. Since there is not more accurate information on the measurement setup, it is hard to tell the reason behind the difference. For example, the windings may have been connected so that a phase shift occurred between the induced voltages, which would cause the total winding factor for the fundamental to be lower and reduce the total amplitude.

In generator short circuit, the third harmonic voltage is induced into both of the windings since the winding factor is also one for the full-width H_1. A short-circuit simulation with FCSMEK gave a value of 0,084 T for the amplitude of the third harmonic flux-density component in short circuit. Using this, Equation (3.15) gives a value of 95 V for the amplitude of the total short-circuit voltage of the auxiliary winding. The measured amplitude, 100 V, is very close to the theoretical value.

Construction 3

In the simulation of Construction 3, the winding factors of windings H_1 and H_3 for the fundamental were 0,793 and 0,383, respectively. The total winding factor of the auxiliary winding for the fundamental obtained using Equation (3.16) was 0,440. Summing Equations (6.14) and (6.15) gives 12,1 V for the amplitude of the voltage in no-load and load operation. Since the windings are not exactly connected in phase, a more accurate value of 9,0 V is obtained using the total winding factor. The simulated amplitude in no-load operation was 7 V.

The winding factor of H_3 for the third harmonic component was 0,924. The simulated third harmonic flux-density component in short circuit was 0,17 T and Equation (3.51) gives 5,3 V for the amplitude of the induced voltage. The simulated amplitude in short circuit was 4 V.

The analytical values in both no-load and short-circuit operation are over 20 % higher than the simulated values. This may cause the analytical program to calculate an insufficient number of auxiliary winding turns which would cause the excitation demand not to be reached. The difference between the analytical values and the voltages measured in the future can be taken into account in the program by adding a possibility of a manual input for correction factors for voltages in both load and short-circuit operation. Using these factors, the calculated number of auxiliary winding turns can be scaled to produce the needed voltage better.

7 Discussion

This thesis presented the operation and design of low-voltage synchronous generator excitation implemented with an auxiliary winding. The theoretical background for the excitation, the selected solution and the principles of dimensioning the auxiliary winding were discussed.

In auxiliary winding excitation principle, air-gap flux-density harmonics induce a voltage in an auxiliary winding wound into the stator slots together with the main winding of the generator. The auxiliary winding supplies power to an automatic voltage regulator that controls the field current of a direct current supplied excitation machine. This enables control and regulation of the terminal voltage of the generator.

A theoretical approach was taken to study the sources of the air-gap flux-density harmonics. Simplifications and Fourier-analysis were used to obtain an approximation of the fundamental and third flux-density harmonic. However, to be used directly as a tool in the design of a harmonic excitation system of a synchronous generator, the analysis would have to be made in a more detailed way to have appropriate results. For example, saturation and harmonics caused by stator slots should be taken into account.

Different auxiliary winding constructions in a certain low-voltage synchronous generator were examined to compare the results and discuss the advantages and disadvantages in different windings. Simulations were performed using finite-element method to compare the waveforms of the voltages induced into the auxiliary winding in different operating states.

The simulated voltage appeared to contain a high distortion level caused by higher order flux-density harmonic components. Some of the harmonics may be caused by the inaccuracy of the simulation program and may not appear in the auxiliary winding of a real machine. Some methods to lower the higher order harmonics in synchronous generators exist, but could not be taken into account in the simulation program. For example slot skewing could be used to lower the harmonic contents of the flux density.

One of the examined solutions was accepted to be used in harmonic excitation of low-voltage synchronous generators. The selection was based on the simplicity of the solution and the possibility to design the excitation separately for load and short-circuit operation. The design of the selected auxiliary winding solution was implemented as a MATLAB code that was compiled into a binary file. The main parts of the calculation process needed in the design were presented.

In the future, interfaces to existing design tools should be created to achieve an effective and simple design process for the auxiliary winding and the whole excitation system. The calculation of the third harmonic flux-density component in generator short circuit should be implemented in the program or a table of pre-calculated values for machines of different frame sizes should be included instead.

Measurements of the voltage waveforms in the selected auxiliary winding could not be made since this work took place in the beginning of the low-voltage synchronous generator development process and a prototype machine could not be manufactured during this work. In the future, proper measurements in both no-load and short-circuit operation will give important information on both the magnitude and waveform of the voltage induced into the auxiliary winding. The design program can relatively easily be modified to take into account the possible differences between the theoretical and measured results.

The solution for the automatic voltage regulator system was also studied. Using two different supply frequencies sets requirements for the operating principle of the automatic voltage regulator. Instead of a thyristor-bridge rectifier, the auxiliary-winding supplied regulator should be implemented with a line-commutated diode-bridge rectifier supplied direct-current chopper converter. If thyristors were used, the use of two different frequencies and harmonic contents in the supply voltage could cause problems with the firing of the thyristors.

Since the auxiliary winding is dimensioned separately for short-circuit operation, no current transformers or a separate excitation current limiter are needed to obtain excitation power or prevent overexcitation and to lower the short-circuit current. Also, when low-voltage synchronous generators are considered, there is necessarily no need for transformers for voltage measurement due to low terminal voltages. Thus the minimum automatic voltage regulator solution in an auxiliary-winding excited low-voltage synchronous generator becomes very simple.

As a whole, one potential solution for the excitation of a low-voltage synchronous generator was implemented during this work. Similar solutions have not been in use at ABB Oy, Electrical machines in Helsinki before, and no accurate information on other auxiliary winding solutions were available. More information on the applicability of the selected solution will be gained after manufacturing and measurements.

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Derivation of flux-density harmonics

The air-gap flux density is obtained as the product of the mmf caused by the windings and the air gap permeance:

$$b = \frac{1}{\tau_p L'}\left[\hat{v}_{s,1}\cos\left(\pi\frac{x}{\tau_p} - \omega t - \phi_s + \beta\right) - \sum_{h=1}^{\infty}\hat{v}_{F,h}\cos\left(h\pi\frac{x}{\tau_p} - h\omega t\right)\right]\times$$
$$\times\left[\Lambda_0 + \sum_{h=1}^{\infty}\hat{\Lambda}_h\cos\left(2h\pi\frac{x}{\tau_p} - 2h\omega t\right)\right]. \qquad (A1.1)$$

Substituting harmonics with $h \leq 3$ to Equation (A1.1) yields

$$b = \frac{1}{\tau_p L'}\left[\hat{v}_{s,1}\cos\left(\pi\frac{x}{\tau_p} - \omega t - \phi_s + \beta\right) - \hat{v}_{F,1}\cos\left(\pi\frac{x}{\tau_p} - \omega t\right) - \right.$$
$$\left. - \hat{v}_{F,3}\cos\left(3\pi\frac{x}{\tau_p} - 3\omega t\right)\right]\left[\Lambda_0 + \hat{\Lambda}_2\cos\left(4\pi\frac{x}{\tau_p} - 4\omega t\right)\right]. \qquad (A1.2)$$

Separate the terms:

$$b = \frac{\hat{v}_{s,1}\Lambda_0}{\tau_p L'}\cos\left(\pi\frac{x}{\tau_p} - \omega t - \phi_s + \beta\right) -$$
$$- \frac{\hat{v}_{F,1}\Lambda_0}{\tau_p L'}\cos\left(\pi\frac{x}{\tau_p} - \omega t\right) -$$
$$- \frac{\hat{v}_{F,3}\Lambda_0}{\tau_p L'}\cos\left(3\pi\frac{x}{\tau_p} - 3\omega t\right) +$$
$$+ \frac{\hat{v}_{s,1}\hat{\Lambda}_2}{\tau_p L'}\cos\left(\pi\frac{x}{\tau_p} - \omega t - \phi_s + \beta\right)\cos\left(4\pi\frac{x}{\tau_p} - 4\omega t\right) - \qquad (A1.3)$$
$$- \frac{\hat{v}_{F,1}\hat{\Lambda}_2}{\tau_p L'}\cos\left(\pi\frac{x}{\tau_p} - \omega t\right)\cos\left(4\pi\frac{x}{\tau_p} - 4\omega t\right) -$$
$$- \frac{\hat{v}_{F,3}\hat{\Lambda}_2}{\tau_p L'}\cos\left(3\pi\frac{x}{\tau_p} - 3\omega t\right)\cos\left(4\pi\frac{x}{\tau_p} - 4\omega t\right).$$

Since the product of two cosines gives

$$\cos x_1 \cos x_2 = \frac{1}{2}\left[\cos(x_1 + x_2) + \cos(x_1 - x_2)\right] \qquad (A1.4)$$

for $x_1, x_2 \in \mathrm{R}$, the last three terms in Equation (A1.3) can be written as

$$\begin{aligned} b = {} & \ldots + \\ & + \frac{\hat{v}_{\mathrm{s},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\left[\cos\left(5\pi\frac{x}{\tau_\mathrm{p}} - 5\omega t - \phi_\mathrm{s} + \beta\right) + \cos\left(-3\pi\frac{x}{\tau_\mathrm{p}} + 3\omega t - \phi_\mathrm{s} + \beta\right)\right] \\ & - \frac{\hat{v}_{\mathrm{F},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\left[\cos\left(5\pi\frac{x}{\tau_\mathrm{p}} - 5\omega t\right) + \cos\left(-3\pi\frac{x}{\tau_\mathrm{p}} + 3\omega t\right)\right] \\ & - \frac{\hat{v}_{\mathrm{F},3}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\left[\cos\left(7\pi\frac{x}{\tau_\mathrm{p}} - 7\omega t\right) + \cos\left(\pi\frac{x}{\tau_\mathrm{p}} + \omega t\right)\right]. \end{aligned} \tag{A1.5}$$

Separating the fundamental and third harmonic components yields

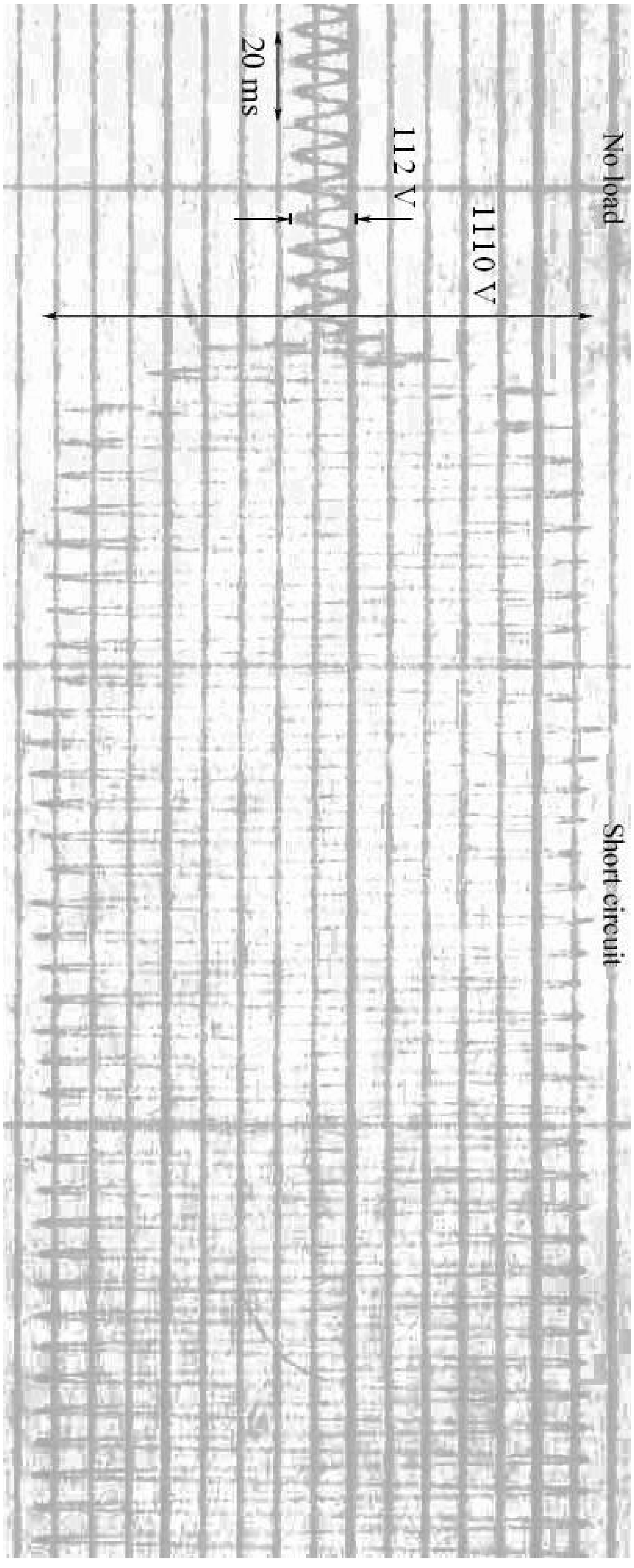
$$\begin{aligned} b_1 = {} & \frac{\hat{v}_{\mathrm{s},1}\Lambda_0}{\tau_\mathrm{p} L'}\cos\left(\pi\frac{x}{\tau_\mathrm{p}} - \omega t - \phi_\mathrm{s} + \beta\right) \\ & - \frac{\hat{v}_{\mathrm{F},1}\Lambda_0}{\tau_\mathrm{p} L'}\cos\left(\pi\frac{x}{\tau_\mathrm{p}} - \omega t\right) \\ & - \frac{\hat{v}_{\mathrm{F},3}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\cos\left(\pi\frac{x}{\tau_\mathrm{p}} - \omega t\right) \end{aligned} \tag{A1.6}$$

and

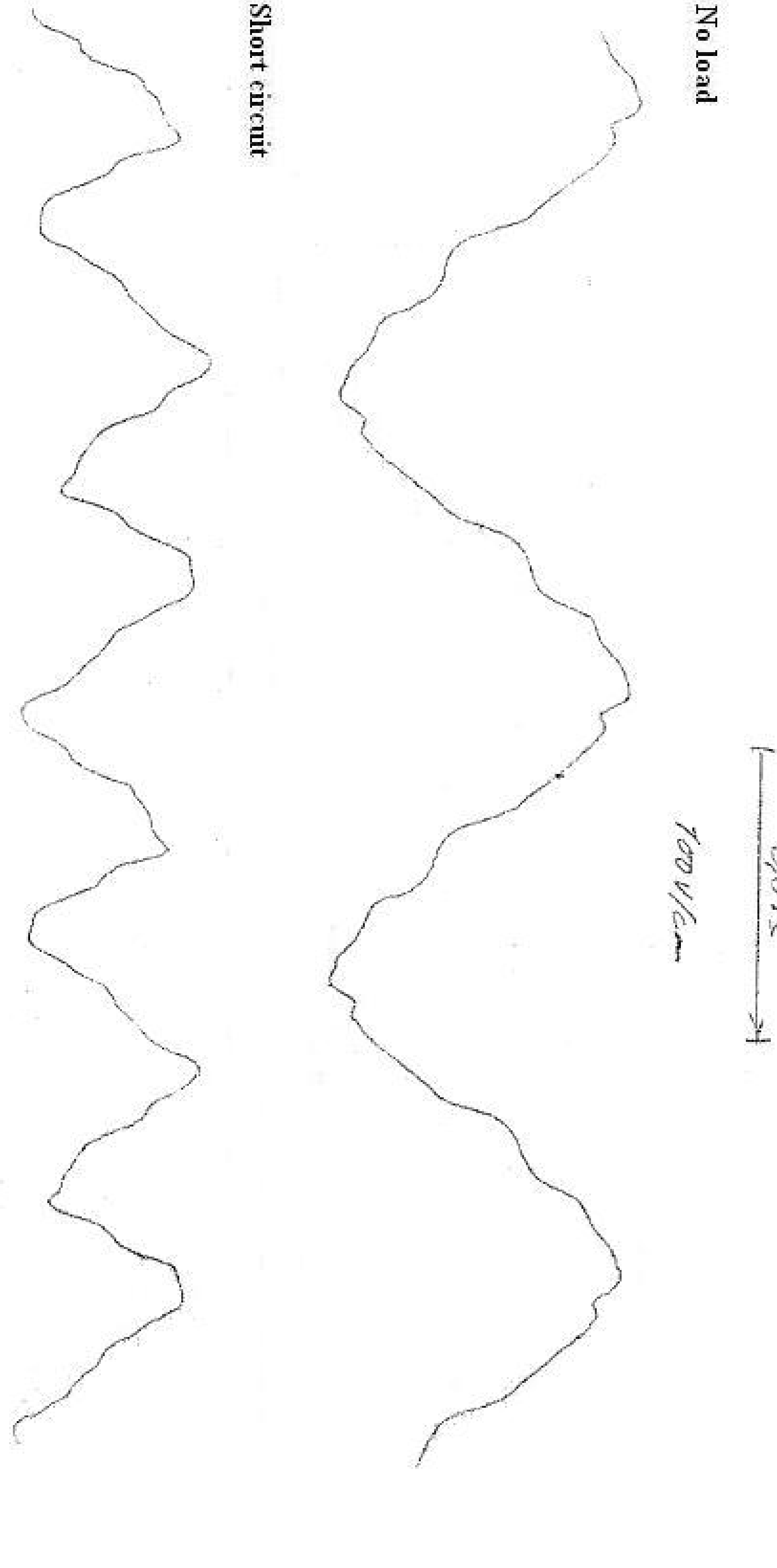
$$\begin{aligned} b_3 = {} & -\frac{\hat{v}_{\mathrm{F},3}\Lambda_0}{\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t\right) + \\ & + \frac{\hat{v}_{\mathrm{s},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t + \phi_\mathrm{s} - \beta\right) \\ & - \frac{\hat{v}_{\mathrm{F},1}\hat{\Lambda}_2}{2\tau_\mathrm{p} L'}\cos\left(3\pi\frac{x}{\tau_\mathrm{p}} - 3\omega t\right). \end{aligned} \tag{A1.7}$$

Voltage waveform measurements

Construction 1

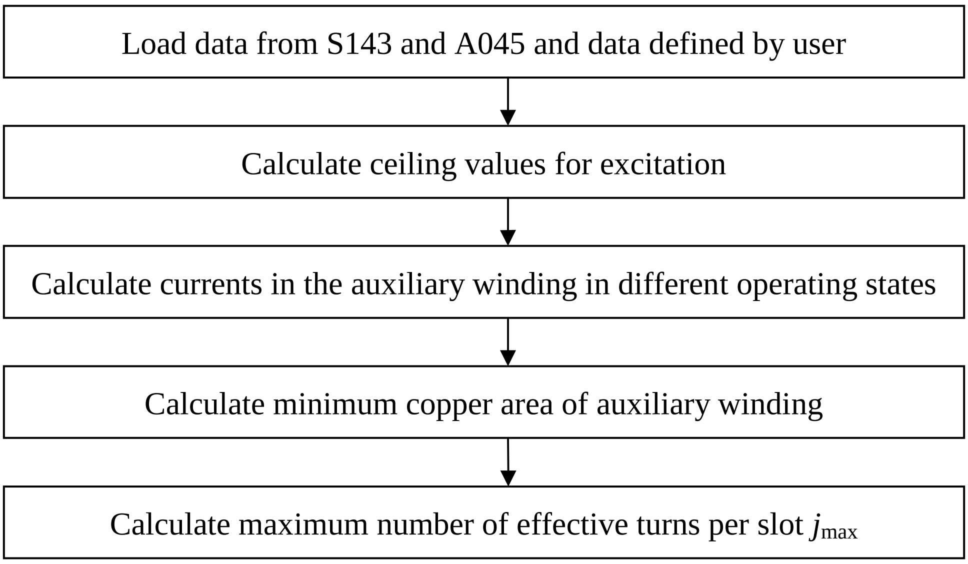


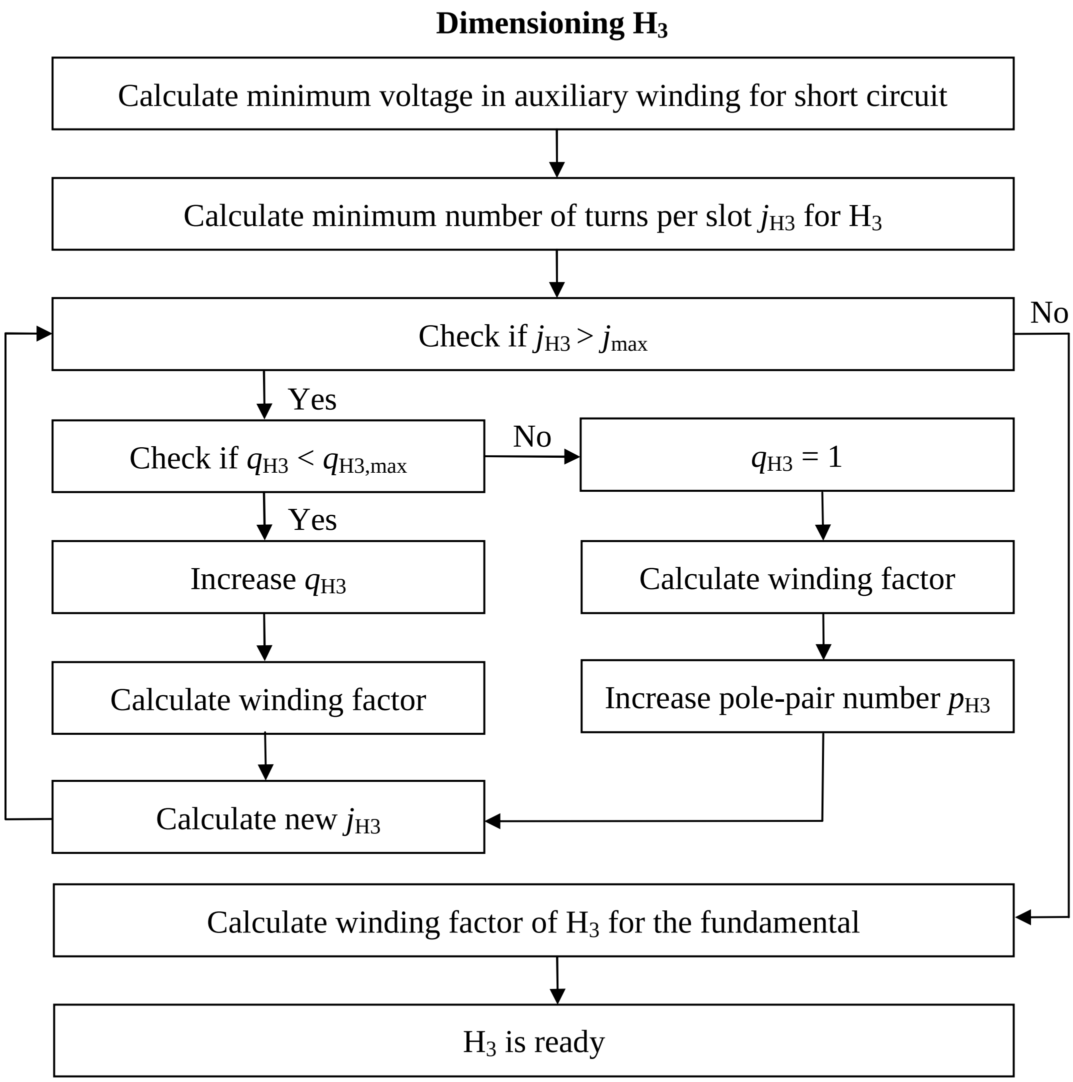
Construction 2



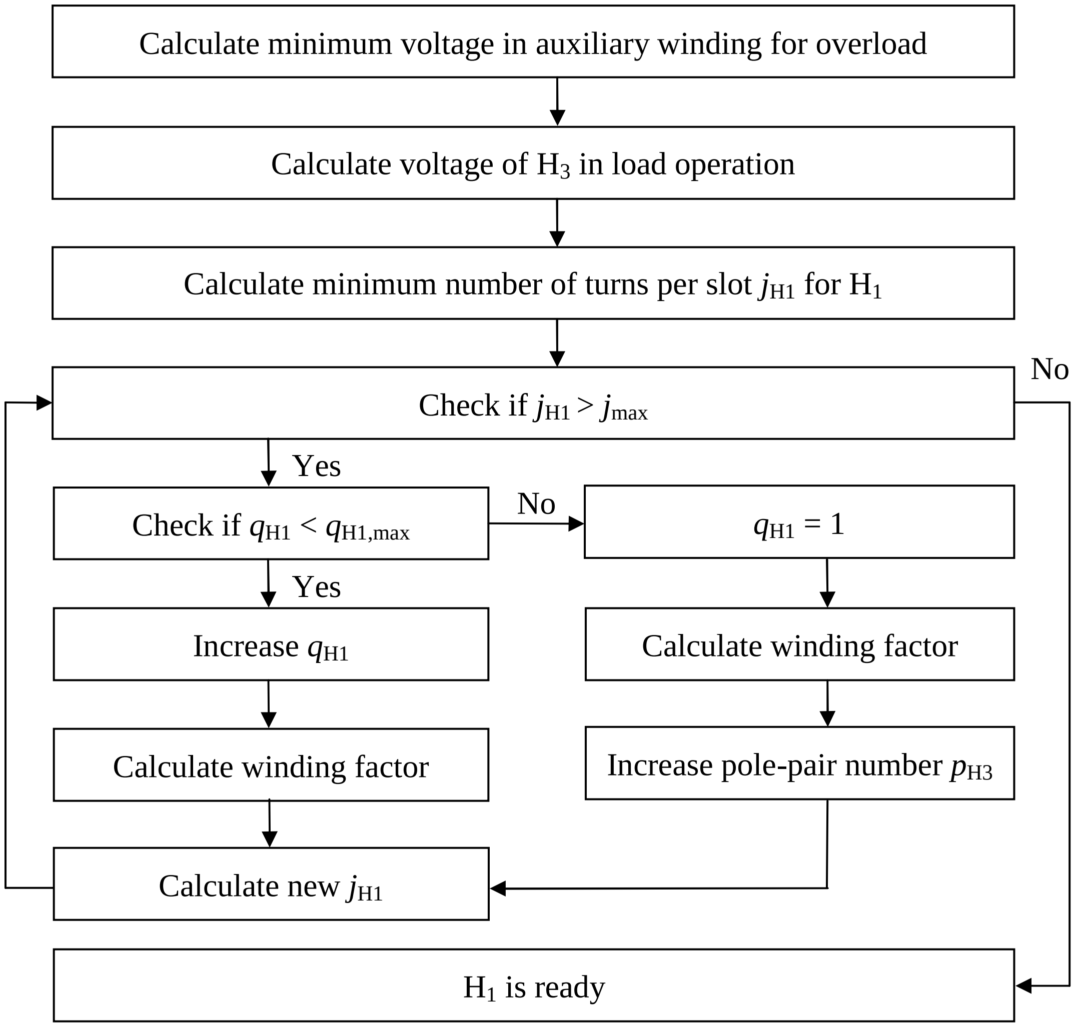
Calculation diagram for auxiliary winding

Calculating initial values for design




Dimensioning H_3
Calculate minimum voltage in auxiliary winding for short circuit
Calculate minimum number of turns per slot j_{H3} for H_3
Check if $j_{H3} > j_{max}$
No
Yes
Check if $q_{H3} < q_{H3,max}$
No
$q_{H3} = 1$
Yes
Increase q_{H3}
Calculate winding factor
Calculate winding factor
Increase pole-pair number p_{H3}
Calculate new j_{H3}
Calculate winding factor of H_3 for the fundamental
H_3 is ready

Dimensioning H_1



Design program output example

```
Data for auxiliary winding
11.6.2007 at 10:06 am
----------------------------------------------

Auxiliary winding requirements:
 Voltage in short circuit:         242 V
 Voltage in overload:              132 V
 Supply voltage of AVR:            180...250 V

Limits for current density:
 Maximum in short circuit:         10 A/mm2
 Maximum in overload:              10 A/mm2
 Maximum in normal load:            8 A/mm2

Maximum number of turns per slot:   3

----------------------------------------------

Conductor:
 Chosen copper diameter:           1.25 mm
 Current density in short circuit:  9.24 A/mm2
 Current density in overload:      6.17 A/mm2
 Current density in normal load:    5.98 A/mm2

----------------------------------------------

Dimensions of H3:
 pole pairs:      2
 slots per pole:  2
 turns per slot:  3

----------------------------------------------

Voltage of H3 in short circuit:     237 V
Voltage of H3 in load operation:    92 V

Voltage in load operation too low for
overload situation. Voltage is raised by
connecting H1 in phase.

----------------------------------------------

Dimensions of H1:
 pole pairs:      2
 slots per pole:  1
 turns per slot:  2

----------------------------------------------

Voltage of the auxiliary winding in load operation 139 V
```

```
Auxiliary winding diagram
11.6.2007 at 10:06 am
--------------------------
A, B, C main winding
X winding H3
Y winding H1
--------------------------
Slot     Bottom  Top     Aux
1       -A       A       X
2       -A       A       X
3        C       A
4        C       A      -X
5        C      -C      -X
6        C      -C
7       -B      -C
8       -B      -C
9       -B       B       X
10      -B       B       X
11       A       B
12       A       B      -X
--------------------------
13       A      -A      -X
14       A      -A
15      -C      -A
16      -C      -A
17      -C       C      -Y
18      -C       C
19       B       C
20       B       C
21       B      -B
22       B      -B
23      -A      -B
24      -A      -B       Y
--------------------------
25      -A       A       Y
26      -A       A
27       C       A
28       C       A
29       C      -C
30       C      -C
31      -B      -C
32      -B      -C      -Y
33      -B       B
34      -B       B
35       A       B
36       A       B
--------------------------
37       A      -A
38       A      -A
39      -C      -A
40      -C      -A
41      -C       C
42      -C       C
43       B       C
44       B       C
45       B      -B
46       B      -B
47      -A      -B
48      -A      -B
```