RIGA TECHNICAL UNIVERSITY

Aleksandrs MESNYAYEVS

USAGE OF MATHEMATICAL MODELING FOR SPECIAL PURPOSE SYNCHRONOUS MACHINE'S MAGNETIC SYSTEM INVESTIGATION AND OPTIMIZATION

Summary of doctoral thesis

Riga 2012

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Power Engineering

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Doctoral student of the program "Electrical machines and apparatus"

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DOCTORAL THESIS
PROPOSED FOR ACHIEVING DR. SC. ING. DEGREE AT
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CONFORMATION

Hereby I confirm that I have worked out the presented Doctoral Thesis, which is submitted for consideration at Riga Technical University for the degree of Doctor of Engineering science. This work is not submitted in any other university for obtaining doctor' degree.

Aleksandrs Mesnyayevs …………………………….(Paraksts)

Date: ………………………

Work is written in Latvian language, it contains preface, 7 chapters, conclusions and main work results, bibliography, 2 appendixes, 71 figures. Total amount of this work 169 pages. Bibliography includes 76 used literatures sources.

Contents

1. GENERAL DISCRIPTION OF THE THESIS

1.1. Topicality of the thesis

While using modern alternative current (AC) network with 50 Hz frequency it is not expedient to apply autonomous power sources with increased frequency. Economically more beneficial is to convert 50 Hz AC into AC with increased frequency. To fulfill this task the synchronous reactive frequency converter (SRFC) can be used.

SRFC's advantages:

- no-contact;
- reactive;
- single machine unit;
- sinusoidal exit voltage;
- easy to make of commercial asynchronous machines.

Increased frequency current usage of in hand tools can give significant economical effect. For example, increased frequency hand tools are lighter (in comparison with pneumatic) for 25-35%, in addition the have higher technical-economical ratios.

To fully use those advantages, that increased frequency network appliance, it is necessary to work out theoretically based and practically applicable SRFC's modeling (design and main parameters selection) and optimizing method. It is necessary to develop electromagnetic field theory based mathematical models and simulation principles to improve this equipment.

1.2 Aim of thesis, its subject and the task of investigation

This doctoral thesis is dedicated to synchronous machines with special construction - synchronous reactive frequency converter's magnetic system's optimization questions, which are based on modern methods and technical resources.

Objective of this doctoral thesis is optimization of specific synchronous machine based on magnetic field's simulation results and this results usage for developing a SRFC.

Object of research is a SRFC which coverts can convert supply frequency f_1 into 2, 3, 4 and theoretically more times (practically is justified only in specific circumstances) higher frequency.

To achieve those goals following tasks are solved in doctoral work:

- Choice and justification of magnetic field's mathematical modeling using finite element method (FEM);
- Managed analysis and recommendations are worked out for rational stator's windings formation;
- Mathematical modeling results processing method with this method's adaptation to "classical synchronous machines theory" is worked out;
- Managed experiments for specific synchronous machines characteristics.

1.3. The methods of research

Solution of mentioned tasks is carried out using finite element method for magnetic field investigation, developing and improving software for SRFC's characteristics determination.

Calculation results are compared with experimental data, which are received in laboratory of Riga Electric Machine Building Works (JSC RER) and in laboratory of Riga Technical University (RTU) Power and Electrical Engineering faculty.

1.4. Scientific novelty of the work

- Adaptation of electromagnetic field's theory for research of special purpose synchronous machines;
- Usage of FEM, which allows to take into account magnetic system's constructive parameters and saturation;
- Synchronous machines of specific importance magnetic field's mathematical simulation method (using stationary field equations);
- SRFC's stator winding's parameter selection and argumentation;
- SRFC's specific form of magnetic field synthesis;
- SRFC's optimization method and magnetic system's optimal parameter determination.

1.5. Practical value of the work

- SRFC's designing framework are worked out;
- Advanced and improved small power synchronous machine's experiment stand;
- Software for magnetic field simulation results automatic processing, as well as for SRFC optimization software tools are developed.

1.6. Realization of work results

The author has presented results of the research at international scientific conferences both in Latvia and abroad:

- A. Mesņajevs, A. Zviedris Determination and Analysis of Synchronous Motor's Parameters. RTU 49. starptautiskā zinātniska konference. 14.09.2009-16.09.2009, Riga, Latvia.
- Mesņajevs, A. Zviedris, A. Podgornovs Determination of Synchronous Machine's Parameters Steady State from Results of Magnetic Field's Mathematical Simulation. Problems of Present-Day Electrotechnics-2010, 31.05.2010 - 04.06.2010, Kiev, Ukraine.
- Mesņajevs, A. Zviedris, Mathematical Simulation of the Magnetic Field Occurred by the Armature Reaction of the Synchronous Machine. 24th European Conference on Modelling and Simulation, 01.06.2010 - 04.06.2010, Kuala Lumpur, Malaysia.
- Mesņajevs, A. Zviedris, Mathematical Simulation, Determination and Analysis of the Magnetic Field Occurred by the Armature Reaction of the Synchronous Machine. 11th International Conference on Environment and Electrical Engineering, 08.05.2011 - 11.05.2011, Roma, Italia.
- Mesņajevs, A. Zviedris, A. Podgornovs Determination of Synchronous Machine's Characteristics Based on the Results of the Mathematical Modelling of the Magnetic Field. 25th European Conference on Modelling and Simulation, 07.06.2011 - 10.06.2011, Krakow, Poland.

- Mesņajevs, A. Zviedris Salient Pole Synchronous Machine`s Mathematical Simulation Data`s Processing Methods. The Sixth International Scientific Symposium on Electrical Power Engineering, 21.09.2011 - 23.09.2011, High Tatras, Slovakia.

1.7. Author's publications

Authors research results are published in 6 international scientific publications (indexed in such data bases as IEEE-EXPLORE).

- A. Mesņajevs, A. Zviedris Determination and Analysis of Synchronous Motor's Parameters. RTU zinātniskie raksti, Enerģētika un elektrotehnika, sērija 4.,. sējums 25., 51.-56. p.
- Mesņajevs, A. Zviedris, A. Podgornovs Determination of Synchronous Machine's Parameters Steady State from Results of Magnetic Field's Mathematical Simulation. Problems of Present-Day Electrotechnics-2010: XI International Scientific Conference, 1. – 6. p.
- Mesņajevs, A. Zviedris, Mathematical Simulation of the Magnetic Field Occurred by the Armature Reaction of the Synchronous Machine. Simulation Meets Global Challenges, 93. - 97. p.
- Mesņajevs, A. Zviedris, Mathematical Simulation, Determination and Analysis of the Magnetic Field Occurred by the Armature Reaction of the Synchronous Machine. 11th International Conference on Environment and Electrical Engineering, 414. - 417. p.
- Mesņajevs, A. Zviedris, A. Podgornovs Determination of Synchronous Machine's Characteristics Based on the Results of the Mathematical Modelling of the Magnetic Field. 25th European Conference on Modelling and Simulation, 175. - 180. p.
- Mesņajevs, A. Zviedris Salient Pole Synchronous Machine`s Mathematical Simulation Data`s Processing Methods. Elektroenergetika 2011, 142. – 145. p.

1.8. Structure of the thesis

1.9. Thesis's volume

Doctoral thesis is written in Latvian, consists of introduction, 7 chapters, summary and main result, references, 2 appendixes, 71 figures, in total 169 pages. Reference list consists of 76 bibliographical indexes.

2. OUTLINE OF THE THESIS

2.1. Introduction

Increased frequency current usage of in hand tools can give significant economical effect. For example, increased frequency hand tools are lighter (in comparison with pneumatic) for 25-35%, in addition the have higher technical-economical coefficient (operation efficiency coefficient for pneumatic tool in average is 0.09, but increased frequency tool – 0.55), increased frequency tool's actual cost is 8-10 times smaller than pneumatic hand tools, operation costs are 7-8 times smaller. Specific power for electrical drills with universal collectormotor is 30-65 W/kg, with three-phase asynchronous motor (50 Hz) is 20-40 W/kg, but for increased frequency electrical drill 50 – 110 W/kg.

While using modern AC network with 50 Hz frequency it is not efficient to apply auxiliary power sources with increased frequency. Economically more efficient is to convert 50 Hz AC into increased frequency AC with frequency converter.

Frequency converter is electrical current frequency changing equipment. This equipment is used in electrically controlled drive and in magnetic amplifier's supplying systems; to harmonize various frequency AC systems work.

Frequency converters are divided into:

- static;
- electro machine;
- combined.

Big popularity receives brushless synchronous reactive frequency converter, which are based on magnetic field deformation in air gap of synchronous reactive machine. In such converters motor and generator part are combined in one magnetic circuit. In rotor exists only short-circuited starting winding without sliding contacts.

Synchronous machine with salient pole rotor and without excitation winding is called reactive synchronous machine. This machine, while working in motor mode rotating moment is produced due to different magnetic conductivity in direct axis and quadrature axis. Connecting reactive machine stator's windings to three-phase AC network a rotating magnetic field is produced. This field is produced due to consumed reactive lagging current.

SRFC is synchronous reactive machine, which uses magnetic field's higher harmonics. In slots of SRFC two windings are placed: primary, which is connected to industrial frequency AC network and secondary, which is used to receive higher frequency. It is possible to note, that synchronous reactive frequency converter is one-machine aggregate, in which the synchronous reactive motor (stator's primary winding – salient pole rotor) and inductor generator (salient pole rotor – secondary winding) are combined

Primary winding is consuming magnetizing current, which produces rotating magnetic field in the air gap. From induction's distribution curve the necessary higher harmonic is used due to specific form rotor magnetic system and to accordingly selected sir gap's width.

This harmonic induces increased frequency EMF in secondary winding. To achieve this secondary winding's step must be equal to necessary field's higher harmonic pole pitch (or almost equal).

SRFC, which scheme is presented on figure 2.1.1., is used, for example, to convert tree-phase AC with voltage 380/220 V and frequency 50 Hz to tree-phase AC with voltage 36V and 200 Hz frequency.

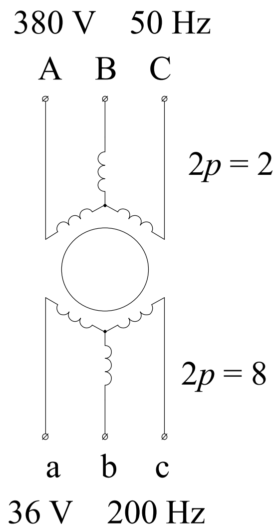


Fig. 2.1.1. Stator winding's scheme

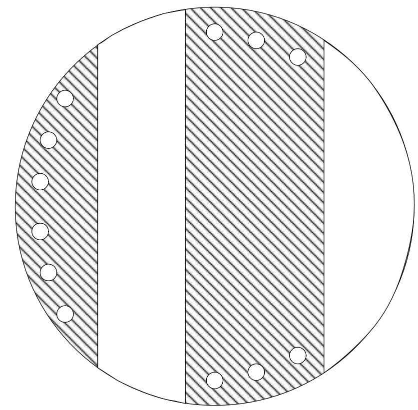


Fig. 2.1.2. Rotor's cross-section view

On figure 2.1.2. rotor's cross-section view is presented schematically. Rotor's parts that are made of ferromagnetic material are marked with stripes; unmarked parts are made of nonmagnetic material (aluminium, plastic). To star rotation in rotor's magnetic part starting winding ("squirrel cage" shaped, made from aluminium bars and short-circuit rings) is placed. When rotor rotates with synchronous rotation speed due to reactive moment it is dragged into synchronous mode. A rotor under load is rotating synchronously with magnetic rotating field (as reactive synchronous motor), because of that AC's increased frequency is constant.

2.2. Basic elements of the electromagnetic field theory are researches of magnetic fields of electric machines

In doctoral thesis's first chapter is proposed to substitute electromagnetic field's equation system with one equation connected to vector magnetic potential (VMP) A and to reduce this equation to several simpler tasks, which describe electromagnetic field with stationary field equation

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu j_a \,. \qquad (2.2.1)$$

where μ – magnetic permeability, j_a – external field sources current density.

After determination of VMP distribution on the surface of the stator it is possible to perform determined characteristics harmonic analysis with aim to receive fundamental and higher harmonic VMP amplitude and phase values.

In this case fundamental harmonic's EMF determine

$$E_1 = 4{,}44 f_1 k_{w1} \frac{2 p_1 q w_{sp}}{a} 2 A_{1m} l \,. \qquad (2.2.2)$$

where f_1 – fundamental harmonic's frequency; k_{w1} – winding's distribution coefficient; q – slot number per pole and phase; w_{sp} – coil's turn numbers; a – parallel branch number; A_{1m} – VMP amplitude value.

In the same way the higher harmonics EMF are determined. In last equation winding's data and corresponding VMP amplitude value must be inserted.

Main results:

- Transition from electromagnetic field's equation system to usage of stationary field's equation to describe in space and time varying magnetic field.
- Usage of FEM together with vector magnetic potential to determine EMF.

2.3. Determination of synchronous machine's main parameters using phasor diagrams

In doctoral thesis's second chapter the inductive reactance's determination method and with this method associated difficulties (for example saturation influence) are described. To consider, approximately, the saturation influence following phasor diagrams are used

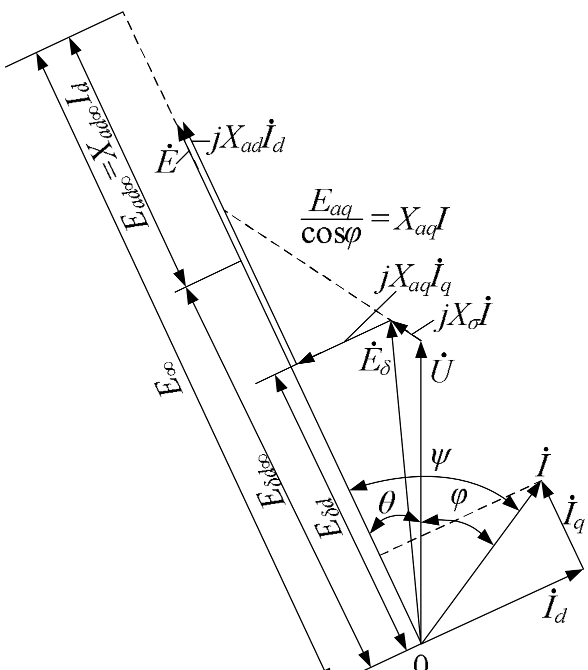


Fig. 2.3.1.Saturated synchronous machines voltage phasor diagram

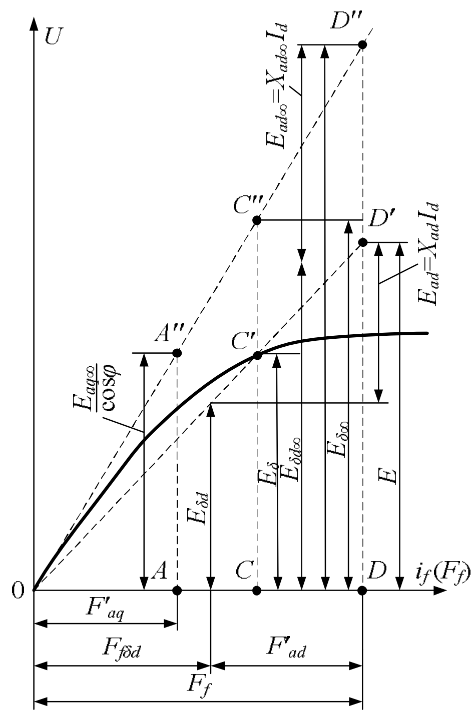


Fig. 2.3.2. Salient pole synchronous generator's EMF determination (taking into account saturation influence)

As is known, the operating mode of the synchronous machine can be described in four parameters: an armature voltage U, an armature current I, a phase angle between these values φ and an excitation current I_f. Analyzing and studying characteristics of synchronous machines it is useful to use these four values, further on not connecting them with two-reaction parameters X_{ad}

and X_{aq}. The mentioned values are easily measured and experimentally checked. Taking into account these reasons it is possible to use the phasor diagram shown on Fig. 2.3.3. On which simultaneously with time-dependent sizes $\dot{U}$, $\dot{I}$, $\dot{E}_\delta$, φ, excitation windings, an armature winding and the resultant MF of the fundamental harmonic's space vectors $\dot{F}_a$, $\dot{F}_f$ and $\dot{F}_\delta$ are shown.

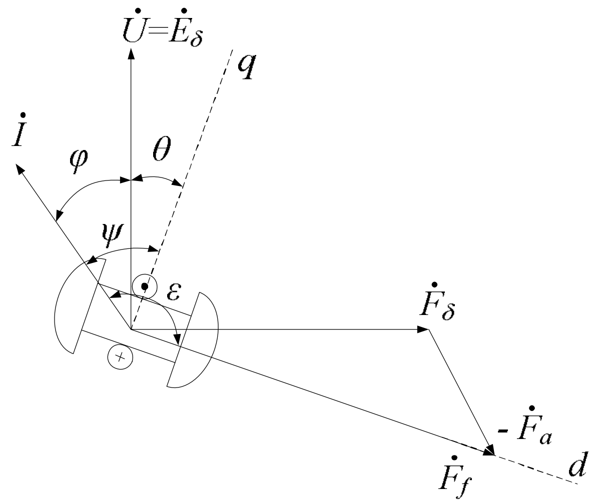


Fig. 2.3.3. Phasor diagram of synchronous machine (engine mode)

Main results:

- Usage of phasor diagram to take into consideration the saturation influence.
- Transition to phasor diagram which doesn't use inductive reactances X_{ad} and X_{aq}.

2.4. Description of experimental model and experimental research's plan

To confirm results received by mathematical modeling three phase two pole synchronous machine, which is made of commercially produced single phase synchronous generator ГАБ-2-0/230, is used.

The aim of experiments it to determine synchronous machines direct-axis synchronous inductive reactance X_{d}, and then to compare received values with from magnetic field's mathematical modeling received.

Experiment program:

- Determine:
  a. no-load characteristic;
  b. short-circuit characteristic.
- From experimental results:
  a. determine direct-axis synchronous inductive reactance X_{d}.

Experiments were conducted in laboratory of Riga Electric Machine Building Works (JSC RER) using there available equipment.

To determine synchronous generator's characteristics on figure 2.4.1. shown shame were used.

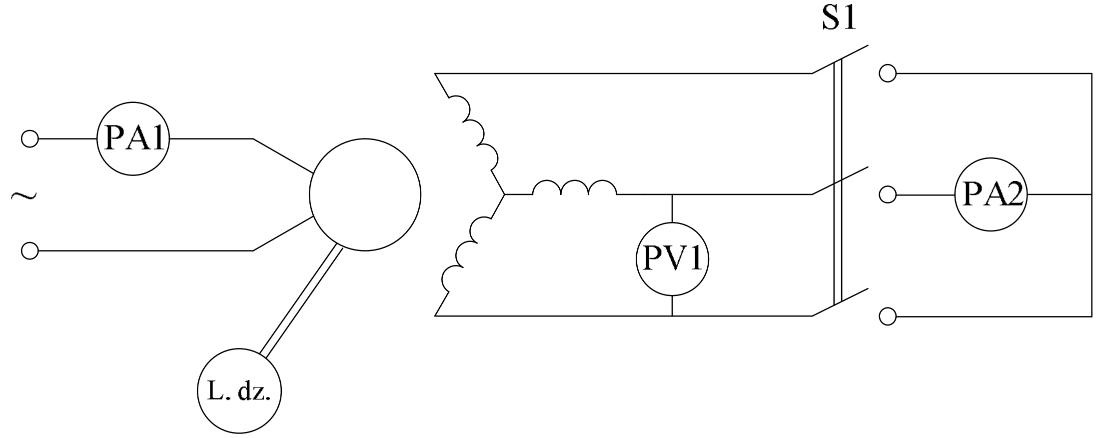


Fig. 2.4.1. In experiment used shame

2.4.1.table

No-load characteristic

I_f , A	U_1, V
12	162
10	154
8	147
6	134
4	114
2	76
1	42
0	0

2.4.2.table

Short-circuit characteristic

I_f, A	I_1, A
6	9,2
5	8
4	6,8
2,5	4,5
1	2
0	0

2.4.3. table

Synchronous inductive reactances calculated using JSC RER received data

I, r.v.	X_d , Ω
1.0	14.56
0.8	15.62
0.6	16.76

Main results:

- No-load and short-circuit characteristic are determined.
- Using no-load and short-circuit characteristic synchronous inductive reactance X_d values for different excitation currents are calculated.

2.5. Numerical modeling of magnetic field using FEM results for determination of synchronous machines parameters

The aim of research in this chapter is to determine of synchronous machine's direct-axis X_d and quadrature-axis X_q inductive reactances taking into account the saturation.

To solve this task calculation process is divided into several stages:

a. Construction of salient pole synchronous machine's mathematical model using *QuickField* software;
b. Receiving of mathematical modeling results (VMP distribution);
c. Determination of one pole magnetic flux (direct-axis Φ_d and quadrature-axis Φ_q) form results of mathematic modeling;
d. Flux linkage with armature vending phase (Ψ_d and Ψ_q) determination form one pole flux;
e. EMF E_d and E_q effective values determination;
f. Determination of synchronous direct-axis X_d and quadrature-axis X_q inductive reactances;
g. Comparison of determined inductive reactance X_{d} values with from JSC RER received direct-axis X_d synchronous inductive reactances.

Magnetic systems saturation can be assessed from figure 2.5.1. shown curves $E_d = f(I^*)$ and $E_q = f(I^*)$.

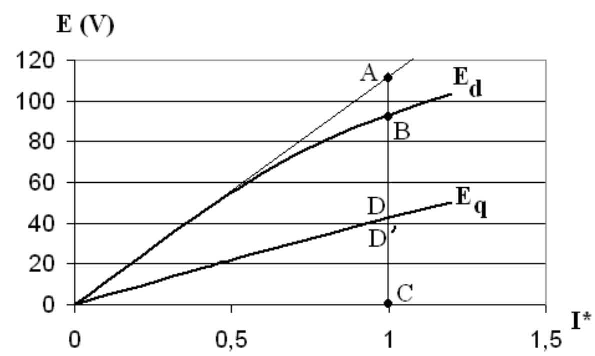


Fig. 2.5.1. Armature winding EMF dependence from armature current (in relative units)

In figure 2.5.1. it is shown that curve $E_q = f(I^*)$ is almost linear. This means, that saturation influence is minimal and $k_{\mu q} \approx 1$.

2.5.1. table

Inductive reactance's dependence form by armature current caused saturation degree

I^*	X_d (Ω)	X_q (Ω)	X_d/X_q	$k_{\mu d}$	$k_{\mu q}$
0.4	16.93	6.65	2.55		
0.6	16.53	6.64	2.49		
0.8	15.42	6.59	2.34		
1.0	14.22	6.49	2.19	1.22	1.02
1.2	13.14	6.34	2.07		

Received direct-axis synchronous inductive reactances X_d values are compared with from JSC RER received values. Comparison results are presented in table 2.5.2.

2.5.2. table

Synchronous inductive reactances comparison

I, r.u.	X_d, Ω (RER)	X_d, Ω (FEM)	Mistake (%)
1.0	14,56	14,22	2,42
0.8	15,62	15,42	1,32
0.6	16,76	16,53	1,41

Remark: (RER) – reactances determined using RER received data, (FEM) - reactances determined using finite element method.

Main results:

- Using in first chapter described material with mathematical modeling results EMF E_d and E_q dependence from armature current are determine.
- In second chapter proposed phasor diagram is applied to salient pole synchronous machine's magnetic field study.
- Using in second chapter described material saturation coefficients $k_{\mu d}$ and $k_{\mu q}$ are calculated.
- Saturation influence on parameters X_d and X_q can be assessed with saturation coefficients $k_{\mu d}$ and $k_{\mu q}$. In design books coefficient's $k_{\mu d}$ and $k_{\mu q}$ proposed boundaries $k_{\mu d} = 1.2 \div 1.5$ and $k_{\mu q} = 1.0 \div 1.2$) are equal to received $k_{\mu d} = 1.22$ and $k_{\mu q} = 1.02$.
- In third chapter received (real synchronous machines) X_d values are compared with calculated values using mathematical modeling results. Mistake is smaller than 3%. This proves that mathematical apparatus works properly.

2.6. Selection of SRFC's constructive elements and parameters

2.6.1. Stator's secondary winding

Salient pole synchronous machines magnetic induction's distribution in air gap is not sinusoidal. Than mean, that magnetic induction curve contains not only fundamental harmonic, bat also higher harmonics. Higher k harmonic's magnetic field in synchronous machines rotates with synchronous rotation frequency and its pole number $2p_k$ is k-times bigger than fundamental harmonic's pole number $2p$. So, to use k harmonic's energy in synchronous machines slots secondary winding with pole number

$$2p_k = 2kp \qquad (2.6.1)$$

and winding pitch

$$y_k \approx \frac{\tau_z}{k} = \frac{Z_k}{2kp}, \qquad (2.6.2)$$

where τ_z –fundamental harmonics pole pitch; Z_k – for secondary winding used slots number, must be inserted.

In this case in secondary winding only with higher harmonic's frequency EMF will be induced. If expression (2.6.2) correctly is taken into account in secondary winding by fundamental harmonic induced EMF will not exist, due to that in this case fundamental harmonic's winding coefficient in secondary winding is equal to zero.

To use k harmonic's energy more efficiently it is important to choose secondary winding shame and parameters correctly. Constructively it is efficient to insert secondary winding in the same slots in which primary winding is placed. If secondary winding is organized as two lair loop winding, it will occupy all Z armature slots. Generally secondary winding can be organized with different phase number m_k. It is necessary to point out, that secondary winding's phase number m_k can't be chosen spontaneously. Phase number depends on stator's primary windings – slots number Z, pole number $2p$ and slots number per pole and pfase

$$q_k = \frac{Z}{2p_k m_k}. \qquad (2.6.3)$$

It is efficient to develop and produce SRFC with this armature winding's parameters: Z = 6…36, $2p$ = 2…8 un q = 0,5…6, q can be as well as whole number and as part number. Its value must match symmetric three phase winding's formation conditions. In case of part number

$$q_k = b_k + \frac{c_k}{d_k}, \qquad (2.6.4)$$

where b_k, c_k and d_k – whole number; $c_k < d_k$ and c_k/d_k are true irreducible part number.

Symmetric three phase winding's formation conditions are

$$\frac{2p_k}{d} = \text{whole number}; \qquad (2.6.5)$$

$$\frac{d}{m_k} \neq \text{whole number}. \qquad (2.6.6)$$

Taking into account all previously mentioned, it is possible to determine winding's parameters with which SRFC can be developed.

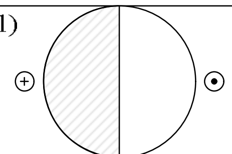
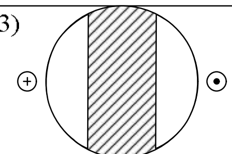
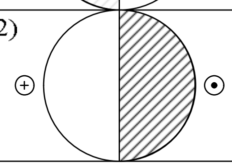
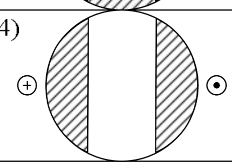
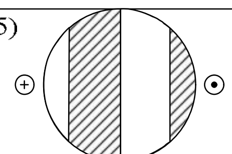
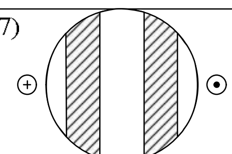
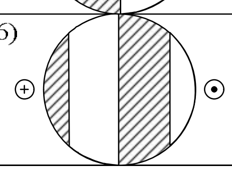
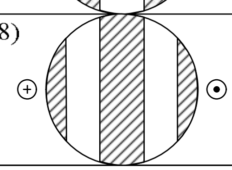
2.6.2. Possible variants of rotors shapes for different f_2/f_1 ratio (2:1, 3:1, 4:1)

For SRFC it is important to exude defined magnetic field's higher harmonic so it will have biggest value. To achieve this rotor's magnetic system's shape and air gap must be chosen that in magnetic field necessary harmonic will be exuded, but all other higher harmonics whenever possible are equal to zero.

Rotor's constructive variants for different harmonic exude are presented on fig. 2.6.1.

2.6.1. table

For different harmonic exude used rotors variants

Exuded harmonic $k = f_2/f_1$ / Exude of harmonic	$k = 2$ (even)	$k = 3$ (uneven)
Using direct-ass conductivity	1) 	3) 
Using quadrature-ass conductivity	2) 	4) 
Exuded harmonic $k = f_2/f_1$ / Exude of harmonic	$k = 4$ (even)	$k = 5$ (uneven)
Using direct-ass conductivity	5) 	7) 
Using quadrature-ass conductivity	6) 	8) 

Choosing rotor's construction for uneven harmonics exude preferable are rotors with quadrature-axis conductivity. In contradistinction to uneven harmonics exude even harmonics can be exuded only with one rotor's shape, for example (see 2.6.1. tab.), because if this rotor is turned by 180° it became equal to rotor with direct-axis conductivity.

2.6.3. SRFC calculation example

GEM is chosen as magnetic field's research method. For research is chosen commercial asynchronous machine's magnetic system, in which slots primary and secondary windings are placed. To clarify SRFC's magnetic system modeling questions and to asses received characteristics the frequency doubler is selected.

The aim of research is to determine in stator's primary and secondary winding induced EMF fundamental harmonics effective values dependence from SRFC rotor's geometrical parameters, rotor's ferromagnetic parts filling angle β (see fig. 2.6.1.) and from armature current.

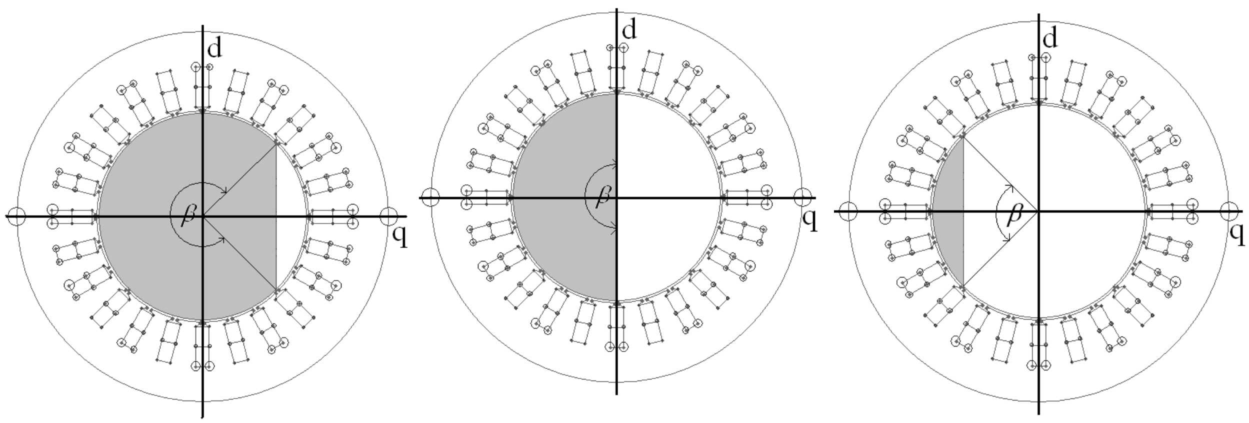
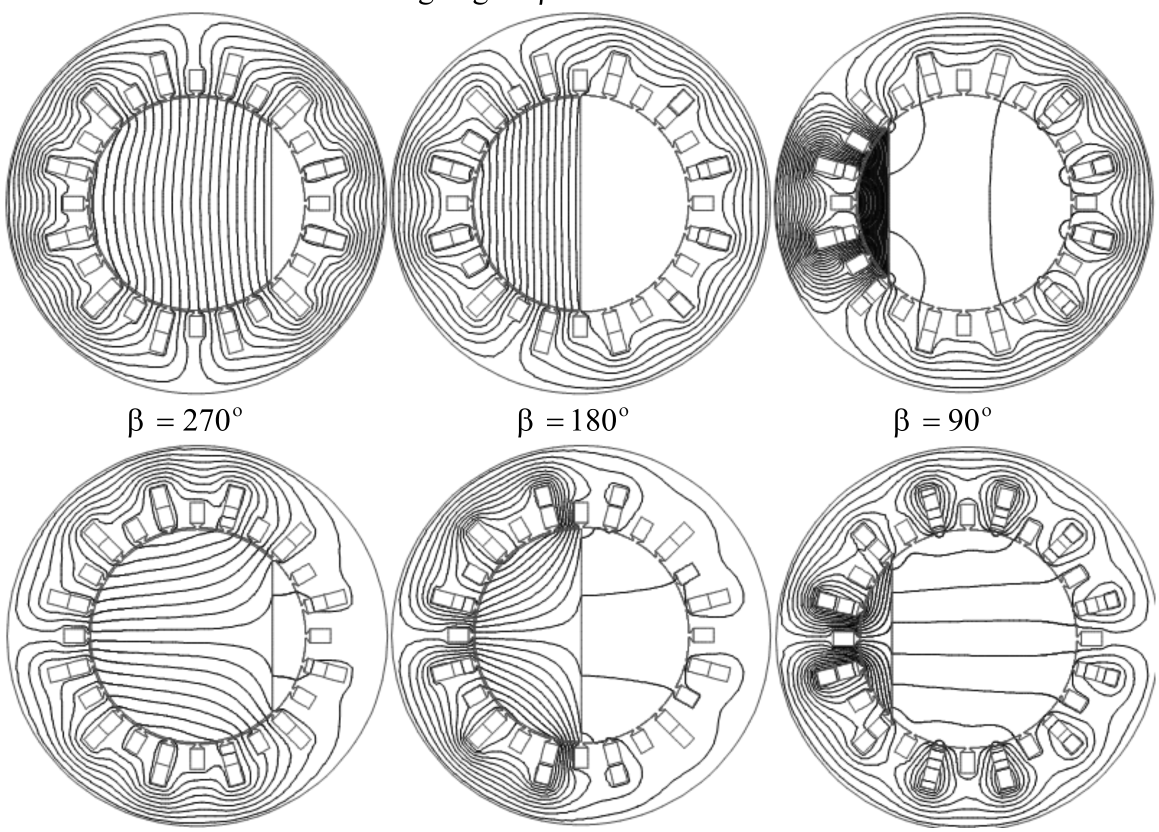


Fig. 2.6.1. SRFC rotor's designs (with gray the ferromagnetic part is shown)

Calculations are made for idle running, when secondary winding's current $I_2 = 0$.

Conducting magnetic field's mathematical modeling the following magnetic field's picture is received for different rotor's filling angles β.



2.6.2. att. SRFC magnetic field's pictures for $I_a = 44$ A

First row – direct-axis ($I_a = I_d$ and $I_q = 0$), second row – quadrature-axis ($I_a = I_q$ and $I_d = 0$)

Received in primary and secondary winding induced EMF fundamental harmonics values (for secondary winding the fundamental harmonic is magnetic field's distribution higher harmonic, in this case 100 Hz) for number of variants:

1. $\beta = 180^{\circ}$ and $I_a = 16,\ 30,\ 44,\ 58,\ 72$ A;
2. $\beta = 90^{\circ},\ 180^{\circ},\ 270^{\circ}$ and $I_a = 16,\ 44,\ 58,\ 72$ A.

Using first variant data results are presented on figures 2.6.3. and 2.6.4.

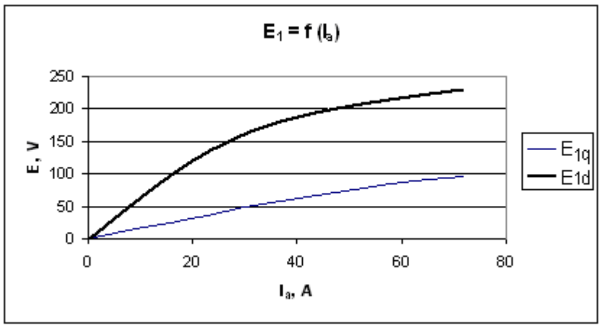


Fig. 2.6.3. In primary winding induced (direct-axis with index *d*, quadrature-axis with index *q*) EMF effective values dependence form armature current for $\beta = 180^{\circ}$

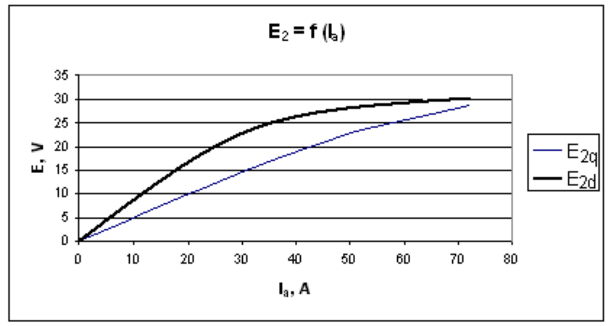


Fig. 2.6.4. In secondary winding induced (direct-axis with index *d*, quadrature-axis with index *q*) EMF effective values dependence form armature current for $\beta = 180^{\circ}$

Using second variant data results are presented on figures 2.6.5. - 2.6.12.

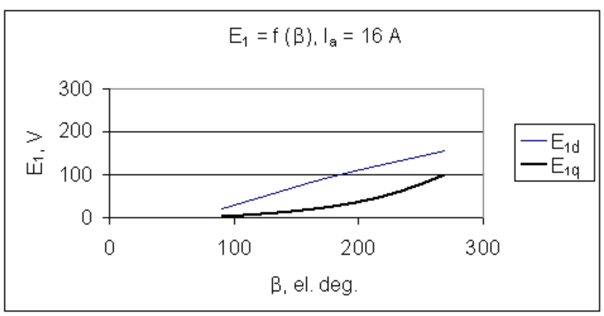


Fig. 2.6.5. In primary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 16$ A in direct-axis and quadrature-axis

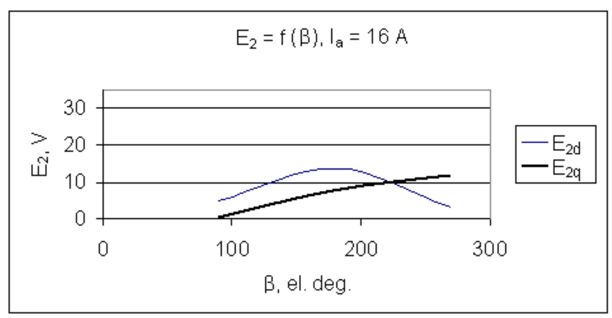


Fig. 2.6.6. In secondary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 16$ A in direct-axis and quadrature-axis

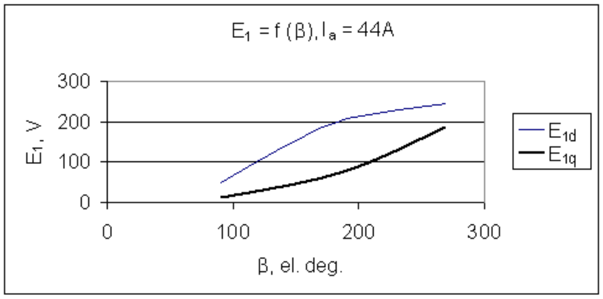


Fig. 2.6.7. In primary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 44$ A in direct-axis and quadrature-axis

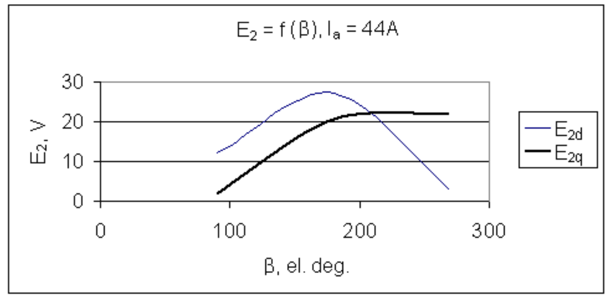


Fig. 2.6.8. In secondary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 44$ A in direct-axis and quadrature-axis

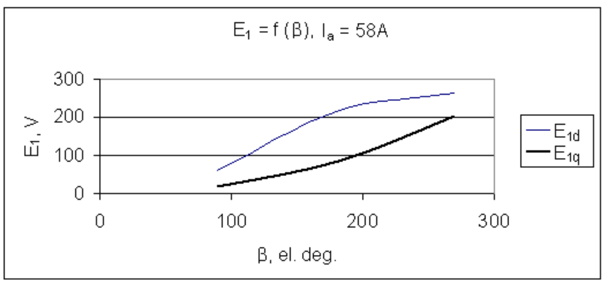


Fig. 2.6.9. In primary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 58$ A in direct-axis and quadrature-axis

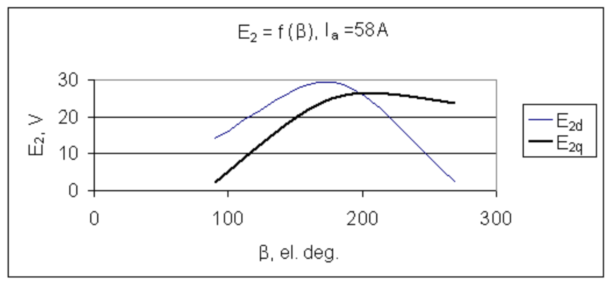


Fig. 2.6.10. In secondary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 58$ A in direct-axis and quadrature-axis

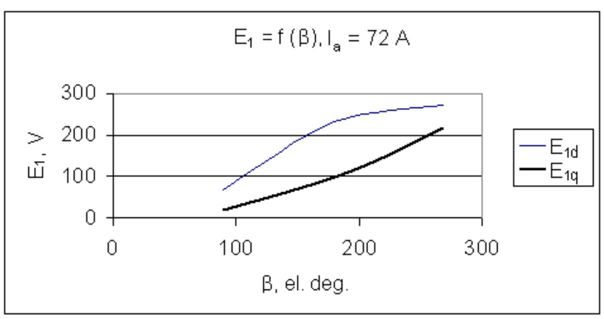


Fig. 2.6.11. In primary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 72$ A in direct-axis and quadrature-axis

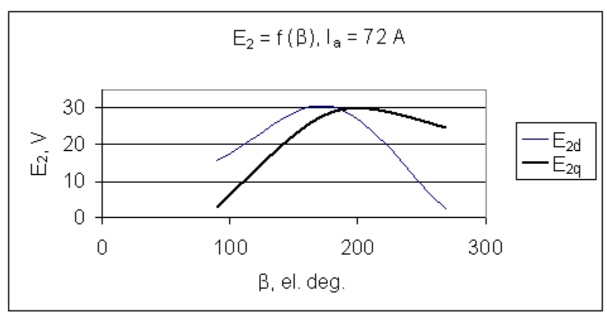


Fig. 2.6.12. In secondary winding induced fundamental harmonic EMF effective values dependence from angle β, if $I_a = 72$ A in direct-axis and quadrature-axis

Main results:

- It is possible to transform commercial asynchronous motor to SRFC.
- SRFC winding's choice base is presented.
- Rotor's designs for different higher harmonic exude are presented.
- Using in first and fourth chapter presented material in primary and secondary winding induces EMF curves are obtained, as well as inductive reactances X_d and X_q dependence from rotor's ferromagnetic parts filling angle β .

2.7. Optimization of SRFC's rotors geometrical dimensions

Research task, that is chosen for optimization is as follows.

Optimization systems boundaries are determined with chosen construction (SRFC with asymmetrical rotor and two windings in stator slots). To decrease variable parameter number it is assumed that geometrical dimensions and winding parameters are known.

For optimization quantitative criteria by second harmonics in secondary winding induced EMF E_2 is chosen (idle running).

For systems independence variables following characteristics are chose: SRFC rotor's ferromagnetic parts filling angle β , armature primary windings current I_a.

For base of development system's mathematical model on magnetic field theory supporting equations, which use FEM are chosen.

The aim of research is to determine in stator's secondary winding induced EMF E_2 dependence from angle β and armature current I_a.

Using *QuickField* software SRFC's model is constructed.

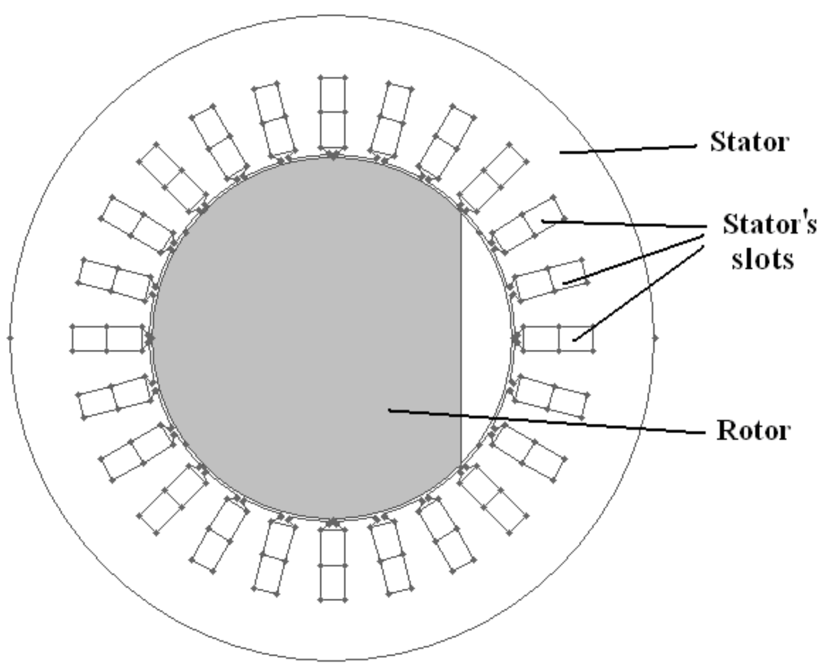


Fig. 2.7.1. SRFC's model

In result of research following charts are obtained.

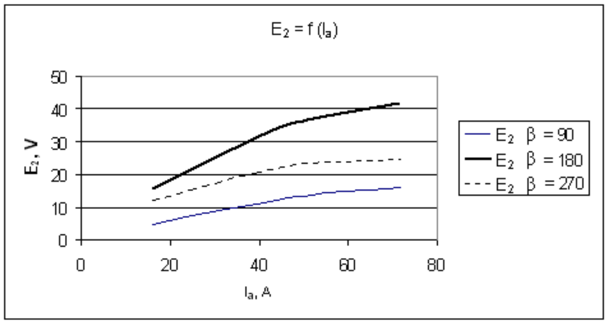


Fig. 2.7.2. In secondary winding induced EMF dependence from armature current if $\beta = 90^{\circ},\ 180^{\circ},\ 270$

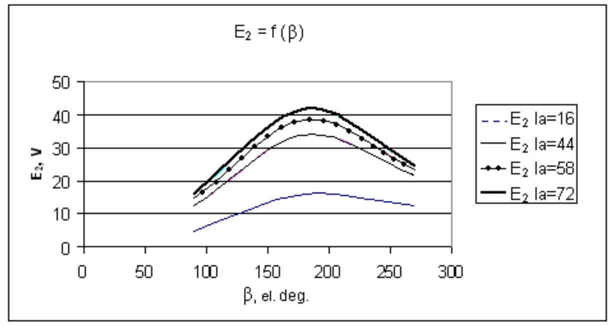


Fig. 2.7.3. In secondary winding induced EMF dependence from rotor's ferromagnetic parts filling angle β

From figure 2.7.2. it is visible, that EMF E_2 curve increases faster when $\beta = 180^{\circ}$.

From figure 2.7.3. it is visible, that highest EMF E_2 value provide β between 180° and 200°.

Main results:

- Using in fifth chapter received results SRFC's optimization is conducted. As result it is can be stated that in order to receive highest in secondary winding induced EMF values frequency doubler must be made of at least 50% from ferromagnetic material, rotor's ferromagnetic parts filling angle β must be between 180° and 200° and armature current must be as high as possible (in feasible constraint).

2.8. Determination of SRFC's parameters

From engineer calculation values shown in 2.8.1. table are known.

2.8.1. table

SRFC's determined characteristics

No-load current's magnetization component	$I_{\mu 1} = 1.854$ A;
No-load secondary winding's phase voltage	$U_{20} = 24.185$ V
Secondary winding's self-induction inductive reactance in direct-axis	$X_{kd} = 4.398\ \Omega$;
Primary and secondary winding's mutual induction inductive reactance	$X_{1kd} = 13.045\ \Omega$;
Primary winding's self-induction inductive reactance in direct-axis	$X_{1d} = 64.196\ \Omega$;
Primary winding's phase active resistance reduced to $t = 75^{\circ}C$	$R_{1\ 75} = 4.903\ \Omega$;
Secondary winding's phase active resistance reduced to $t = 75^{\circ}C$	$R_{2\ 75} = 0.064\ \Omega$.

Values that are presented no figure 2.8.1. are used for SRFC's load characteristics determination. These characteristics are presented in 2.8.2. and 2.8.3. tables. These tables differ with armature current value and load's character (pure active and active-inductive load).

2.8.2. table

SRFC pure active load characteristics

$\cos\varphi_2 = 1$						
I_2, A	$U_{2\ lin}$, V	P_2, W	P_{a1}, W	I_1, A	η	$\cos\varphi_1$
0	41.88965	0	86.62188	1.85864	0	0.070614
5	41.5849	360.1358	451.5577	1.976213	0.797541	0.346207
10	40.65696	704.1991	810.021	2.223419	0.869359	0.55199
15	39.06142	1014.846	1144.667	2.538753	0.886586	0.683148
20	36.71136	1271.719	1435.141	2.857547	0.886128	0.760952
25	33.44811	1448.346	1654.968	3.118494	0.875151	0.804083
30	28.96465	1505.047	1764.469	3.253396	0.852975	0.821738

2.8.3. table

SRFC active-inductive load characteristics

$\cos\varphi_2 = 0.7$						
I_2, A	$U_{2\ lin}$, V	P_2, W	P_{a1}, W	I_1, A	η	$\cos\varphi_1$
0	41.88965	0	86.62188	1.85864	0	0.070614
5	38.17117	330.5721	443.484	2.312972	0.745398	0.290512
10	34.14515	591.4114	744.0094	2.808593	0.794898	0.401371
15	29.80111	774.2556	979.9356	3.286193	0.790109	0.451815
20	25.12022	870.19	1142.348	3.718278	0.761756	0.465493
25	20.07278	869.1768	1221.209	4.092285	0.711735	0.452148
30	14.61359	759.3442	1204.647	4.405217	0.630346	0.414332

As well as with help of FEM several SRFC's inductive reactances are examined. Results are presented in 2.8.4. table.

7.4. table

Inductive reactances received using FEM and engineer calculation

	X_{1d}, Ω	X_{1kd}, Ω	X_{kd}, Ω
FEM calculation	72.99	12.18	4.81
Engineer calculation	63.88	12.99	4.4
Mistake, %	12.48	6.56	8.57

Main results:

- From conducted engineer calculation received inductive reactances are compared with by mathematical modeling determined. It is ascertained that mistake is lower than 13%, which is in allowed engineer calculation mistake boundaries.
- SRFC's load characteristics for different load characters are received.

3. CONCLUSIONS AND MAIN RESULTS

1. "Classic synchronous machine theory" which is based on superposition principle and in which direct-reaction and quadrature-reaction inductive reactances X_{ad} and X_{aq} are introduces in theoretical means isn't correct for saturated machines. There for in several cases doesn't give that advantages which for this theory was created.
2. Using in figure 2.3.1. and 2.3.2. presented phasor diagrams reactances X_{ad} and X_{aq} usage for practical calculations in particular cases is justified. This is proved by experimental results.
3. Analyzing synchronous machines characteristics it isn't useful to connect its parameters with two reaction method, but consequently to use electromagnetic field's theory, which is based on Maxwell equations.
4. Salient pole synchronous machine was examined in order to prove correct work of mathematical apparatus.
5. Received real machines X_d values are compared with from modeling results calculated X_d value. As result mistake isn't larger than 3%. This proves that mathematical apparatus is correct.
6. Given magnetic field's numerical model allow:
   - to design SRFC with necessary higher harmonic;
   - to determine rotor's optimal geometrical shape;
   - to determine load characteristics.
7. Saturation influence on parameters X_{ad} and X_{aq} can be evaluated with saturation coefficients $k_{\mu d}$ and $k_{\mu q}$. In books for designers saturation coefficients are recommended $k_{\mu d} = 1.2 \div 1.5$ and $k_{\mu q} = 1.0 \div 1.2$. Calculated saturation coefficients $k_{\mu d} = 1.22$ and $k_{\mu q} = 1.02$ are in recommended boundaries.
8. To receive the highest in secondary winding's induces EMF value frequency doubler's rotor must be made of at least 50% from ferromagnetic material, rotor's ferromagnetic parts filling angle β must be between 180° and 200° and armature current must be as high as possible (in feasible constraint).